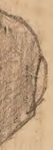
[illegible] first day

Sam Cartini
University of Toledo
K. i.x.

Most [illegible] made up of these

O
Si.
AL
Fe
Ca
Sod
K
Mg



Coarser fine grain by cooling fast or slow

Light colored rock
Quartz & granite

Dark
Diorite
heavy, Fe

Chief [illegible] for these

next test

Next meeting of class Jan 3

about rocks –

by Sid

[illegible] not

674 – 684 – Minerals (Rock faults) [illegible]

98 / 623

Feldspar & quartz [illegible]

Sid [illegible]

Learn

Chap XVII

Superhot Star – written
Globular Star clusters
Spiral Nebulae
Galaxy
Nebular – Planetesimal ~~Hypothesis~~

Hard. to for Tales

FOR THEM READS OR SOMETHING about
Geology. – Cosmic Side   Origin of stars, groups of stars, solar System etc.

Then – get a list of
High Spots in Cosmography Sciences (40)

Chap on ~~Cosh~~ Physics – Entire Chap, XII [329]

Get 25 first subjects of the most valuable
information things studied so far
To be exterior [illegible] Ques
and write essay

of Star
Origin of Earth
world

329 – 8 pages Rocks what becomes of rock.
23 – 2 pages

Page 422 – Metamorphism
35 4 Par.
75 Bottom – Conceptions and chap
171 – 1 Par. boulders.

Read over lesson on Rocks

Topics of Final Exam.

Agency of erosion (12) 15–20 % more
Sand dunes (course) 220 – 233 3 agencies
Basal conglomerates (240) Fig 233
Rate of erosion in N.A. – 9000 yrs
Roaring brooks 91
Deposits at mouth } great rivers 233 –
Minerals in gol – } 8000 yrs. 83

Ice Sheets of Pleistocene Time (651) of existence

~~1. [illegible] Kansan [illegible]~~

1. Aftonian (earliest –
2. Kansan –
3. Illinoian –
4. Iowan –
5. Wisconsin (most important) –
last sheet
Covered Ohio left 25,000 / 30,000 years ago.

Get something for discussion outside of text, for next lesson, about fossils

Rocks - must name rocks & give description next Thur.

Look at some maps that illustrate which part of [illegible] was above or below

Mountains - what is it?

Residual Mat.

Accumulated Mats - 4 kinds

Rock Cycle

Test of Rocks.

[illegible]

[illegible]

[illegible] Sed.

Radio activity, Carbonation Oxidation Hydration, streams, wind, tides, crystalline structure of rock, lightning, waves, earthquakes, Streams, temp.

Extrusive
Volcanoes
Cool [illegible]

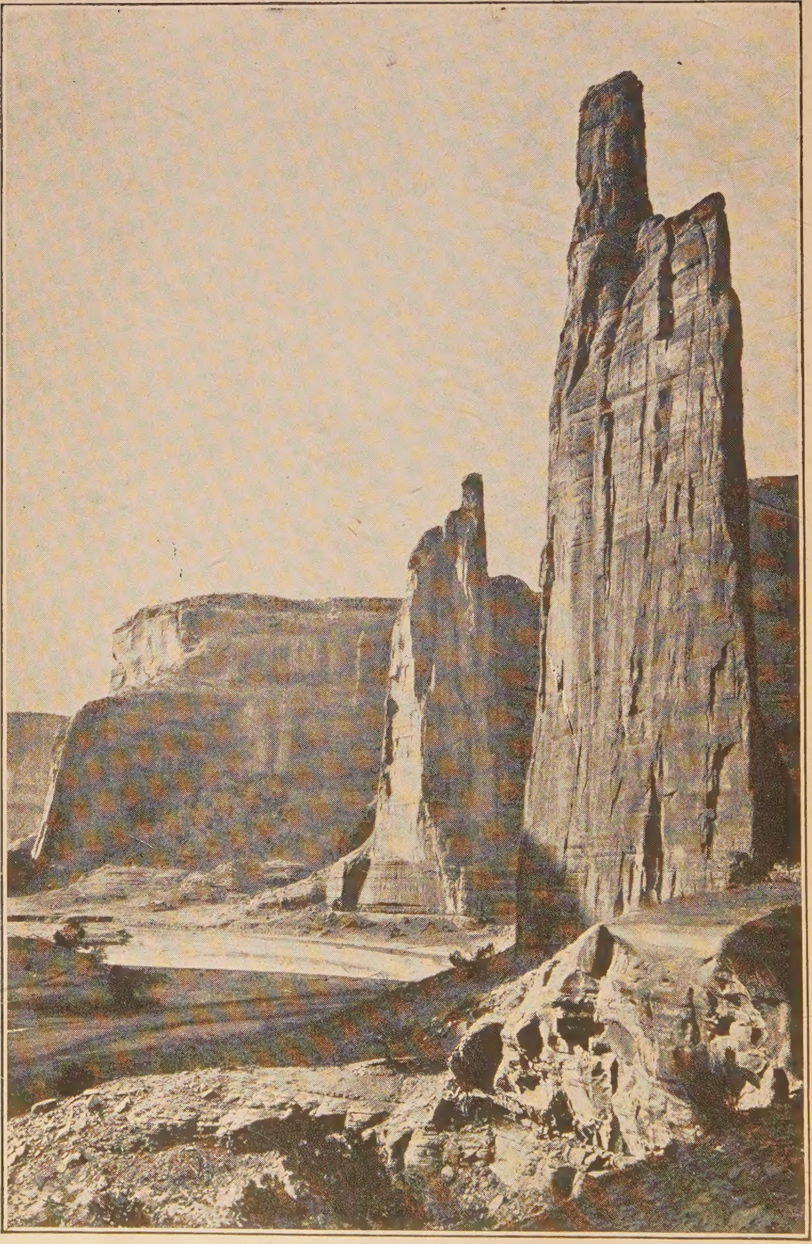


PLATE I. — The Captain of the Canyon, Monument Canyon, Arizona.

160 Paintings of Birds
Am. Nature Ass.
1214 Sixteenth St.
Washington D.C.

R. Bruce
Horsfall
Bird & anim
Paintings

GEOLOGY

PHYSICAL AND HISTORICAL

Hough's Handbook of Trees
Romeyn B Hough Co.,
Lowville N.Y.
very g

BY

HERDMAN FITZGERALD CLELAND, Ph.D.

PROFESSOR OF GEOLOGY IN WILLIAMS COLLEGE
WILLIAMSTOWN, MASSACHUSETTS

L. L. Bean
333 Main St.
Freeport Maine
Get Catalog

Cod oil.
470-478
497-503

AMERICAN BOOK COMPANY
NEW YORK CINCINNATI CHICAGO

CLELAND'S GEOLOGY
W. P. 12

MADE IN U. S. A.

TO
MY MOST HELPFUL CRITIC
AND INDISPENSABLE AID
MY WIFE

PREFACE

In the preparation of this book, an attempt has been made to present an outline of the essentials of modern geology. By avoiding all details not necessary to an understanding of the fundamental principles of the science, it is hoped that this work will prove interesting to the student, although not less accurate because interesting. In the section on physical geology the human relation has been emphasized whenever possible, while in the historical section the history of life from the evolutionist's point of view has been taken up in broad outline.

Much that may prove excellent in this work is due to the help of a number of eminent geologists, whose suggestions and criticisms have added many interesting points and have assisted in the elimination of errors.

The writer wishes especially to express his debt to Dr. W. D. Matthew, of the American Museum of Natural History, City of New York; to Professor Joseph Barrell, of Yale University; and to Professor A. W. Grabau, of Columbia University, upon whom he has freely called for suggestions and criticisms and from whom much valuable assistance has been received.

One or more chapters have also been read and helpfully criticized by the following geologists and educators, and their generous aid is acknowledged with keen appreciation: Messrs. H. E. Gregory, of Yale University; C. K. Schwartz, of Johns Hopkins University; J. B. Woodworth, of Harvard University; J. S. Grasty, of the University of Virginia; N. M. Fenneman, of the University of Cincinnati; Sumner W. Cushing, of the Salem (Massachusetts) Normal School; J. W. Gidley and C. W. Gilmore, of the United States National Museum; T. W. Stanton and F. H. Knowlton, of the United States Geological Survey; Charles Schuchert and G. G. MacCurdy, of Yale University; T. D. A. Cockerell, of Boulder, Colorado; L. Hussakof, of the American Museum of Natural History; E. C. Case, of the University of Michigan; O. P. Hay, of the Carnegie

Institution of Washington; Sidney Powers, Cambridge, Massachusetts; and C. L. Dake, of the Missouri School of Mines.

For suggestions as to the most characteristic species of the various periods, credit is due to Professor G. D. Harris, for the Tertiary; Messrs. T. W. Stanton and F. H. Knowlton, for the Mesozoic; and Drs. R. Ruedemann and E. M. Kindle, and Mr. L. Burling, for the Paleozoic.

The numerous block diagrams which illustrate the text were made in wash rather than in line because the former are not only more attractive in appearance, but because being more realistic, they are more readily understood by the student. These drawings and many of the diagrams which illustrate the text are the work of Mr. G. S. Barkinton, to whom much credit is due.

The writer is greatly indebted to Professors H. F. Osborn, W. B. Scott, F. A. Lucas, and S. W. Williston, for permission to use photographs of restorations of extinct animals, made by them or under their direction, and to Professor William Bullock Clark and Dr. John M. Clarke for the loan of a number of original drawings of the Geological Surveys of which they are directors.

CONTENTS

INTRODUCTION

PART I. PHYSICAL GEOLOGY

CHAPTER I

WEATHERING

CHAPTER II

WORK OF THE WIND

CHAPTER III

THE WORK OF GROUND WATER

CHAPTER IV

THE WORK OF STREAMS

CHAPTER V

THE WORK OF GLACIERS

CHAPTER VI

THE OCEAN AND ITS WORK

CHAPTER VII

THE STRUCTURE OF THE EARTH

CHAPTER VIII

EARTHQUAKES

CHAPTER IX

VOLCANOES AND IGNEOUS INTRUSIONS

CHAPTER X

METAMORPHISM

CHAPTER XI

MOUNTAINS AND PLATEAUS

CHAPTER XII

ORE DEPOSITS

PART II. HISTORICAL GEOLOGY

CHAPTER XIII

HISTORICAL GEOLOGY

CHAPTER XIV

THE EARTH BEFORE THE CAMBRIAN

CHAPTER XV

THE CAMBRIAN PERIOD

CHAPTER XVI

THE ORDOVICIAN PERIOD

CHAPTER XVII

THE SILURIAN PERIOD

CHAPTER XVIII

THE DEVONIAN PERIOD

CHAPTER XIX

THE CARBONIFEROUS PERIODS

CHAPTER XX

THE MESOZOIC ERA: THE AGE OF REPTILES

CHAPTER XXI

CENOZOIC ERA: THE AGE OF MAMMALS. TERTIARY PERIOD

CHAPTER XXII

QUATERNARY

APPENDIX

INTRODUCTION

GEOLOGY is the science that treats of the earth and its inhabitants as revealed in the rocks, and therefore deals with its constitution and structure, with the operation of the forces which led to its present condition, and with the occurrence and evolution of its life. In the search for this knowledge it calls to its aid astronomy, chemistry, physics, and biology. Geology is, in fact, a composite science, making use of the physical sciences in unrolling the complicated history and structure of this planet.

Because of the breadth of its scope, geology has been divided into a number of branches which are, however, in such a large measure interdependent, that a general knowledge of all is often essential to a thorough understanding of any one.

Astronomic or Cosmic Geology. — Since the earth is one of the planets of the solar system, all theories of its origin must at the same time consider the origin of the other planets, and *vice versa*. Consequently, astronomy and geology are dependent upon one another in all attempts at determining the genesis of the earth.

Structural Geology is a study of the materials of which the earth is built and their arrangement, and is especially concerned with the interpretation of the structures produced in the rocks by earth movements. The branch of geology which investigates minerals is *mineralogy*, and that which deals with rocks is *petrology* (Greek, *petros*, rock, and *logos*, discourse). Both mineralogy and petrology are closely allied to chemistry and optical physics.

Dynamical Geology is a study of the agencies that have produced geological changes, together with their laws and modes of operation. Among the most important forces considered are water in motion, wind, glaciers, igneous activity, and earth movements resulting from strains. This branch of the subject is closely related to *physiographic geology*, since the latter deals with the evolution of the topography of the earth's surface and with the forces which have produced it. A study of physiographic geology is necessary to an interpretation of land surfaces.

Industrial Geology includes *mining* and *economic geology* and is the commercial application of geological principles.

All of the above subjects are included in Part I of this volume, under the head of *Physical Geology*.

Historical Geology includes *paleontology* (Greek, *palaios*, ancient, *ontos*, living being, and *logos*, discourse), or the study of the life of the past as shown by its fossil remains; or, in other words, fossil botany and zoölogy. It also embraces *paleogeography* (the geography of prehistoric lands), which is concerned with the boundaries of the lands and seas of the epochs and periods of the past, and with the evolution of the continents. It also includes *stratigraphy*, or the arrangement and succession of the strata, as indicated mainly by fossils. Historical geology calls to its aid all other branches of geology, in order that the topography of the ancient land surfaces and the boundaries of the lands and seas may be known, and that the climates to which the earth was subjected may be determined. Such an exhaustive study is necessary, since the causes of the rapid extinction of certain forms of life, and of the sudden appearance and evolution of others, cannot be known with certainty until the environment under which they lived is learned.

In general, it may be said that *Historical Geology* deals with the evolution of the continents and of the life of the past.

Length of Geological Time. — Without an appreciation of the vastness of geological time (p. 417) as compared with the brief span of a man's life, the work accomplished by the various geological agents cannot be understood. This conception of the length of geological time can, perhaps, best be grasped by a comparison: "Let a year be represented by a foot; the average length of a human life is then measured by the breadth of a dwelling house, and human history is limited approximately to a mile; but the duration of geologic time is comparable to the circumference of the globe."

Present Status of Geology. — Much of the science of geology is definitely known and has been learned as a result of the accurate observation and careful reasoning of many geologists. It should, however, be borne in mind that many of the theories are subject to change, as will be pointed out from time to time in the following chapters. This is due to the fact that geology deals with many problems concerning which our knowledge is as yet incomplete, notwithstanding careful observations and deductions. For example, before it was known that the crust of the earth is heated, to some extent, as a result of the radioactivity of certain minerals, a correct theory of the earth's interior was impossible. The true theory has probably not yet been found, but every advance in knowledge brings the solution nearer. The modification of geological theories from time to time should not be a source of annoyance to the student, but should rather serve to stimulate him to reason for himself.

Fundamental Terms. — There are a few terms with which the student must become familiar before a discussion of the subjects taken up in the following chapters can be understood. Of these terms only very elementary definitions will be given in this place, since more complete explanations will be taken up later.

Rocks. — With the exception of a comparatively thin layer of soil, which varies greatly in thickness and is entirely absent in some places, the earth is composed of rock which extends from the surface downward for many miles (the lithosphere), and probably through the central core (the centrosphere). In general, the rocks of the earth's crust can be classified according to their origin as of three kinds: (1) sedimentary, (2) igneous, and (3) metamorphic.

Sedimentary Rocks. — If one examines the sediment deposited by a muddy rivulet in a temporary pool of water, he will find that it consists of sand or clay, and that it is in layers. This deposition

Fig. 1. — Niagara limestone, showing well-bedded layers with two sets of strong joints at right angles to each other. (U. S. Geol. Surv.)

represents on a minute scale what is occurring in the lakes and oceans of the earth. In the pool the deposit may be only a fraction of an inch thick, while off the shores of the ocean it may be many thousands of feet in depth. When, as has often occurred in the past, such an enormously thick deposit has been raised above the sea and streams have cut deep valleys into it, it is seen to be made up of layers, and the rocks composing it are consequently called *stratified* (p. 233) or layered rocks (Fig. 1). The planes which separate the layers from one another are called *bedding planes* or *planes of stratification*. If the rock is made of hardened mud it is called *shale*, and is usually divided into many thin layers or *laminæ*, the laminæ being separated by planes of bedding. If the rock is composed of sand whose grains are cemented together by lime or other substances, it is called a *sandstone*. Sandstone is also stratified, but the bedding planes are usually farther apart than in shale. Sedimentary rocks are not always in the horizontal position in which they were deposited, but are often folded and tilted.

Igneous Rocks. — Although few persons have seen lava flowing from a volcano, many have seen the molten slag or glass of blast furnaces, which bears a resemblance to lava after hardening, and is, in fact, not unlike the lava of some volcanoes, both in composition and structure. Lava (p. 298) is an igneous rock (Latin, *ignis*, fire); that is, a rock which has been in a molten condition. The majority of igneous rocks, however, are not glassy, but are composed of distinct grains or crystals. This crystalline structure, as we shall learn (p. 302), is brought about when molten rock cools so slowly that time is given for crystals to form. An igneous rock is, therefore, one which solidified from a state of fusion; it is either glassy or grained (crystalline).

It is apparent, therefore, that igneous rocks differ from sedimentary in a number of particulars; the former are either glassy or crystalline and are devoid of stratification planes, while sedimentary rocks are seldom crystalline and are arranged in layers.

Granite is a typical crystalline, igneous rock (Fig. 5, p. 29) and is composed, usually, of three minerals, the most conspicuous of which is feldspar. These feldspar grains or crystals are opaque, and white, pink, or gray in color. Mica, when present in granite, is usually easily recognizable by its glistening leaves which split into elastic scales. The third conspicuous mineral of granite is quartz. It is usually colorless, has the appearance of broken glass, and is harder than steel. A crystalline igneous rock is, therefore, made up of a number of minerals differing in color, in hardness, and in chemical composition. The importance of this character will be seen when the effect of the weather upon rocks is studied.

Metamorphic Rocks are those which have been more or less profoundly changed from their original condition by heat and pressure, and are usually crystalline in *texture*. Most metamorphic rocks possess a cleavage which causes them to break easily in one direction. They are derived both from igneous and from sedimentary rocks. Metamorphic rocks have parting planes like sedimentary rocks, and a crystalline structure like igneous rocks.

Divisional Planes. — All rocks are more or less broken by planes which separate them into blocks. An examination of a sandstone or limestone quarry will show that, in addition to the bedding planes, the rock is broken by two or more sets of fissures which run at right angles to the bedding. These are called joints (Fig. 1). Joints occur also in igneous rocks, some often being approximately horizontal and others tending towards the vertical.

Fig. 2. — A fault. The thin-bedded band was once continuous. (U. S. Geol. Surv.)

When beds are displaced along a joint or other crack so that the strata on the opposite sides of it do not match, the beds are said to be *faulted* (p. 261) (Fig. 2).

Plate II. — A lake resting on the floor of a steep-sided cirque. Lakes of this origin are common in the high mountains of the United States and Canada, where glaciers formerly existed.

PART I. PHYSICAL GEOLOGY

CHAPTER I

WEATHERING

NOTHING endures. The most indestructible rock will, in time, disintegrate; the mountain peaks will crumble away, and the rough places will be made smooth. The forces which produce these results are called the agents of weathering. They vary in their effectiveness in different places and at different times in the same place, but under all conditions and at all times some agent is at work, reducing the exposed rock to soil. The rate at which rock weathers depends largely upon two factors: (1) the composition and structure of the rock, and (2) the physical conditions to which it is exposed. A sandstone (p. 36) in which the grains are held loosely together will disintegrate rapidly, while another, in which the cementing material is insoluble and abundant, may have a long life. The effect of different physical conditions is obvious. In the dry regions of Mexico and Arizona churches and houses built of sun-dried brick (adobe) have lasted for several centuries; houses made of a similar material would, in New England, crumble to a mound of clay in the course of a few years.

MECHANICAL AGENCIES

1. **Frost.** — The property possessed by water of expanding upon freezing is of great importance in the disintegration of rocks in regions where the temperature falls below the freezing point, since upon freezing it expands one tenth and exerts the enormous pressure of 150 tons to the square foot. This force is well illustrated in the bursting of water pipes in which water has frozen. It is stated that in Finland freezing water is sometimes used instead of powder and blocks of stone of 400 tons' weight are broken out in this way.

All rocks, even the most dense, contain pores and fissures in which water may accumulate. Certain sandstones when weighed, then

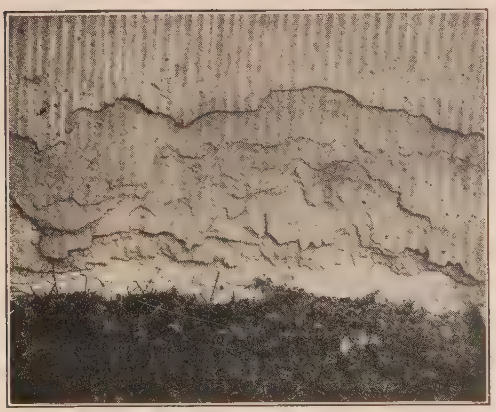


FIG. 3. — Sandstone "set on edge," showing the scaling of the laminæ by frost.

soaked in water for twenty-four hours and again weighed, are found to have gained one eighth in weight. This fact shows not only that pores are present, but also that they have become filled with water. If such a rock, with its pores full of water, is frozen repeatedly, its grains will be forced apart until it finally falls to pieces. This test is used in laboratories to determine the desirability of building stone in temperate regions. The complete disintegration of the rock is not attained by one freezing and thawing, but if the process is repeated many times, the rock may be completely reduced to sand, as the water penetrates farther into the rock each time it thaws. It is readily seen that this *wedge work* of ice is usually more important in moist, temperate regions in early and late winter.

The obelisk which now stands in Central Park, City of New York, stood for many centuries in Egypt without apparent injury (although undoubtedly weakened by the extremes of daily temperature to which it had been so long subjected). But after one year's exposure to the moist, changeable climate of its new home, the hieroglyphics near its base became almost illegible, and it was found necessary to coat the

FIG. 4. — Much-fractured limestone with strong bedding planes, illustrating the conditions favorable for the wedge work of frost and roots. The beds are bent into a low anticline.

monument with paraffine dissolved in turpentine to prevent further decay. Few, if any, tombstones in New England which are over one hundred years old show a polish. A marble slab at North Adams, Massachusetts, for example, upon which an inscription was chiseled in 1865 was practically illegible in 1905 and had to be recut. Such rapid weathering of marble as this is, however, unusual. Tombstones of red sandstone which were erected with the bedding planes[1] on edge have suffered severely, because the rain water has soaked down the more porous layers, and upon freezing has forced off sheets of the rock (Fig. 3). Exposed rock surfaces in polar regions are pulverized by frost, producing sand, and fine, dusty material which is shifted by the winds.

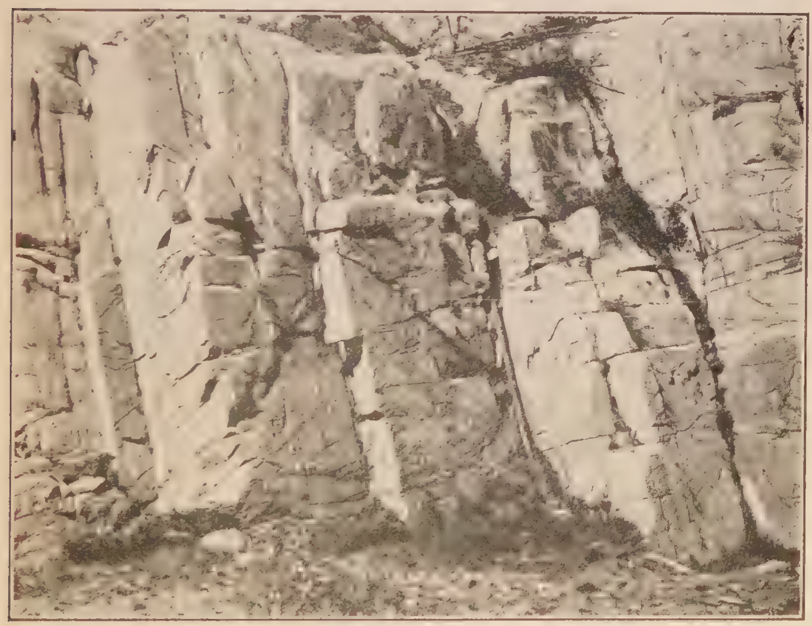


FIG. 5. — Granite broken by two sets of joints. Animas River Canyon, Colorado. (U. S. Geol. Surv.)

Talus.[2] — The most conspicuous effect of frost is seen in rock masses which are much broken by cracks and joints (p. 258) (Figs. 4, 5).

---

[1] When rock is arranged in layers it is said to be *bedded*, and the planes separating the layers are called *bedding planes*. For a discussion of such rocks (stratified rocks) the student is referred to page 233.

[2] Talus slopes produced in arid regions by changes in daily temperatures are also important.

In such cases, blocks are forced from cliffs, building up slopes of loose fragments at their base, called a *talus*. The formation of talus slopes (Fig. 6) can best be studied in the early spring, when fragments of the rock, loosened as the ice in the cracks melts, fall from the cliffs. These fragments are carried down by their weight until the declivity is too gentle for them to roll farther. When they come to rest they accumulate to form a slope, usually steep, whose angle is called "the angle of repose." The slope of a talus (Fig. 14, p. 39) varies from 26 to 43 degrees, the angle depending upon the size of the fragments and upon their shape. If the fragments are angular, the slope will be steeper than if they are rounded, since with the former an early lodgment is more likely. The largest blocks accumulate at the foot of the talus slope, the size diminishing regularly to the top. If talus accumulates under water the slope will be steeper, since the fragments are, to some extent, buoyed up by the water.

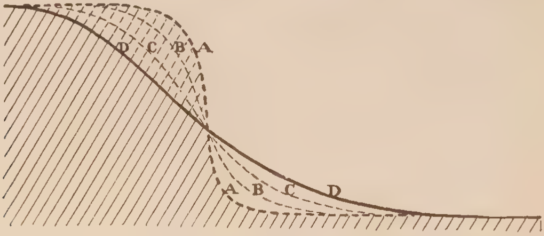


FIG. 6.— Diagram showing the formation of a talus slope and the destruction of a cliff. The successive faces of the cliff *A*, *B*, *C*, *D* and of the talus *A*, *B*, *C*, *D* are indicated by dotted lines.

It is evident that the alternate freezing and thawing of water in the pores and joints of a rock may bring about its complete disintegration unless it is protected by the soil of its own making. It should be remembered, however, that this agent seldom acts alone, but usually serves as an aid to the chemical agencies of weathering (p. 35), by breaking up the rock into small fragments and thus furnishing a larger surface upon which the latter may work.

Rock Glaciers. — A striking example of the above is shown in the formation under favorable conditions of *rock glaciers* or "stone rivers" (Fig. 7), many hundred feet in length in regions of severe cold, when great masses of talus are slowly moved some distance down a valley, producing the appearance of a glacier. This is accomplished by the alternate freezing and thawing of the water in the interstices of the talus.

Creep of Soils. — Another important result of frost action is the *creep of soils* on slopes. If soil contains water, each freezing slightly raises the fragments at right angles to the surface of the hill, and each thawing permits gravity to pull them down hill. If the process is often repeated, the soil moves slowly down the slope. In the course of many years, many tons of earth may be thus carried to a lower level.

FIG. 7. — Rock glacier, McCarthy Creek, Alaska. The talus forming the rock glacier is derived from the high cliffs (cirque). (U. S. Geol. Surv.)

2. Changes in Daily Temperature. — In regions where the air is dry and clear the radiation of heat is rapid and the range in daily temperature is wide, often varying 80° F., while in the Sahara Desert a change of 131° F. within a few hours has been recorded. In such regions, the naked rocks are heated to a high temperature during the day and are cooled rapidly at night. Since rocks are not good conductors of heat, the side of the rock exposed to the sun's rays is often raised to a temperature of 120° F. or more during the day, while a short distance beneath the surface the rock is still cool. The result is that the outside shell is expanded, while the interior is little affected. Strains are thus produced which tend to break off fragments of the rock, dark-colored rocks being particularly affected, since they absorb more heat. In the late afternoon and night, on the other hand, when the temperature falls, the interior which had been gradually acquiring heat during the day is still warm when the surface is cool and contracted. The contracted exterior is then too small for the still expanded interior and the surface of the rocks tends to shell off (Fig. 8), forming onion-like, concentric layers, the process being known as *exfoliation.* It is stated that in certain parts of Africa the rock temperature rises to a height of 137° F. during the day and falls so rapidly at night as to throw off, by contraction, masses as much as 200 pounds in weight. Slabs of granite 8 to 10 inches thick and 10 feet long are known to have been broken off by changes in daily temperature. In the western part of the United States, where the climate is too dry to afford much scope for the operation of frost, cliffs are slowly disintegrated by these changes in temperature, producing talus slopes of large size.

Fig. 8. — Exfoliated granite. (U. S. Geol. Surv.)

The alternate heating and cooling of a rock causes its disintegration in still another way. When a rock is composed of minerals differing in color and composition, it is especially liable to disintegration by changes in daily temperature. Since dark-colored minerals absorb heat more rapidly than light-colored ones and also radiate it more quickly, rocks containing both expand and contract at different rates, with the result that the grains are gradually loosened until the surface is reduced to sand. The fact that the coefficients of expansion of the various minerals differ widely also aids in the disintegration of the rock. Igneous rock,[1] composed of minerals of different kinds, is therefore more easily disintegrated by this process than rocks made up of one mineral.

Changes in daily temperature are especially effective in high alti-

---

[1] Igneous rocks are those which have been formed from molten masses by cooling. See page 329 for a discussion of these rocks.

tudes, and mountain peaks often owe their jagged shapes, to some degree, to this action, although more largely to that of frost. In regions of deficient rainfall, talus accumulates at the foot of cliffs, the fragments forming the slope having been broken off by temperature changes. Mountains in desert regions are sometimes almost buried beneath rock fragments and sand, broken from their sides by changes in daily temperature.

When the heated rocks of arid regions are wet by a sudden downpour, they cool quickly and are broken asunder. In western Texas blocks 25 feet in diameter are reported to have been rent into several pieces in this way. (Hobbs.)

3. **Mechanical Action of Animals and Plants.** — If one observes a cliff upon which vegetation is abundant, he will see that not only the large but also the small cracks of the rock are filled with roots and rootlets. As these roots and rootlets grow larger they tend to push the blocks of rock apart. The root of the garden pea, for instance, has a wedging force equal to 200 or 300 pounds a square inch. Abundant examples of this wedging process can be found in fertile regions, and are also often seen in cities, where the pavements are frequently broken and tilted by the enlarging roots of trees.

Plants, earthworms, and burrowing animals open channels through which water from the surface can reach deep down into the soil. Moreover the organic matter carried into the tunnels by the animals is, upon its decay, a source of organic acids which actively attack the rocks and thus hasten the decomposition of those otherwise protected by soil. It is thus seen that the mechanical disintegration of rocks is accomplished both by the agents of the weather and by organisms.

4. **Rain.** — The mechanical effect of rain consists in (1) the impact of the raindrops upon the surface, which in the aggregate has a considerable effect, as, for example, in gravel deposits where the larger bowlders protect the gravel underneath from the impact of the rain, while that which is not so protected is removed. In the process of time, columns a score or more feet in height may result (Fig. 9). On a small scale, this same result can be seen in almost any soft material after a rain. (2) The mechanical work of rain is seen also in the softening of clay soils, which, on slopes, causes them to creep; (3) in the washing and later deposition of dust from the atmosphere, and (4) in the dissolving of some of the atmospheric gases which may later be used in weathering the rocks. Dew and hoarfrost, being

condensed from the lower layers of the air, absorb and furnish to the soil more gases and inorganic matter than rain. (5) Rain water is also effective in causing certain rocks to swell. In excavating the Panama Canal it was found that certain rocks which, when first uncovered, had to be blasted before they could be removed, became so soft after a few months' exposure to the tropical rains that they could be excavated with the steam shovels. The slides which have occurred in the Culebra Cut were due both to the softening of the rock in this way and to gravity which tends to cause the rock to move toward the excavation. The softening action is taken advantage of in extracting diamonds from the inclosing rock in the South African mines.

Fig. 9. —The work of rain water in sculpturing a bank of earth containing bowlders, near Bogen, Tirol.

5. **Wind.** — The mechanical work of the wind carrying sand is very effective in wearing away rock, especially in arid regions, and will be discussed on another page (p. 45).

6. **Lightning.** — When lightning strikes the earth it sometimes fractures large masses of rock. When it strikes sand, drops or bubbles of glass and irregular tubes or rods are sometimes formed by the partial fusion of the soil. These *fulgurites*, as they are called, are seldom more than a few inches long, but are sometimes several feet in length and two and a half inches in diameter. The entire summit of Little Ararat in western Asia, where electrical storms are extremely common, is said to be drilled by lightning. " A piece of rock about a foot long may be obtained, perforated all over with irregular tubes, having an average diameter of three centimeters. Each of these is lined with a blackish-green glass." (A. Geikie.) This is, however, unusual, and the total effect of lightning is inconsiderable.

CHEMICAL AGENCIES

The chemically active gases of the atmosphere are oxygen and carbon dioxide. Unless they are dissolved in water, however, their effect in the weathering process is unimportant, but in the presence of both moisture and heat they accomplish a great part of the work of chemical decomposition. It is evident, therefore, that the chemical decomposition of rocks must vary greatly in effectiveness in different places and at different times in the same place, and we find that it is most active in moist, tropical regions, less rapid in temperate regions, and least important in the frigid zones and in arid regions.

FIG. 10. — Limestone bowlder channeled by water containing carbon dioxide.

FIG. 11. — Joints in limestone, widened by solution. (Photo. H. L. Fairchild.)

1. **Solution.** — Pure water is a poor solvent, but when it contains a considerable quantity of carbon dioxide its solvent power becomes greatly increased, so that limestone, gypsum, and other easily soluble rocks are slowly taken up by

it and carried away. Water obtains its supply of carbon dioxide from the air, from the decay of plants and animals, and from subterranean sources (p. 296). It has been estimated that the surfaces of certain limestones in England have been lowered at rates varying from one inch in 24 years to the same amount in 500 years. Although solution is most conspicuously exhibited in limestone regions, where the rock is often furrowed by the rivulets (Fig. 10) which flow over the surface, and the joints and other cracks are widened by its action (Fig. 11), it is also effective on feldspar and even on quartz. Sandstones with calcareous cements are disintegrated by the solution of the cement, causing the rock to fall to pieces and form sand. In regions of impure limestone the insoluble residue, such as clay and flint nodules (p. 77), will be left, covering the unweathered rock (Fig. 12). The depth of this cover often gives a basis for estimating the thickness of limestone which has been dissolved and carried away. Many caves are formed by solution (p. 70).

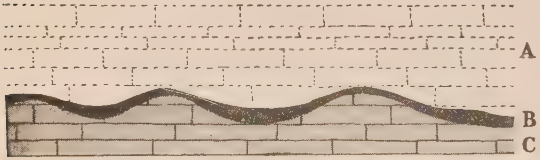


FIG. 12. — The formation of the residual soil *B* from the limestone *A* is shown. The soil was derived from the limestone by the removal of the soluble portions and the concentration of the insoluble. Large areas of Kentucky and Virginia owe their fertility to this process.

2. **Oxidation.** — Oxygen is effective only on rocks which contain minerals capable of taking up further oxygen and thus forming new compounds. The most important of these are iron compounds, and to them the red and yellow coloring, so conspicuous in rocks, is due. If oxygen alone is added to the iron molecule, a red color (Fe_2O_3) results; if moisture is present, however, the brown or yellow rust (hydroxide), common in moist regions, is formed. One noticeable result of oxidation is an increase in volume; this being the case, the newly formed and bulky minerals crowd the grains of the rock apart and tend to produce disintegration. Complex silicates, such as feldspar, mica, and hornblende, are attacked by oxygen and carbon dioxide, and reduced to simpler and more stable compounds.

3. **Hydration.** — The union of water with chemical compounds is known as *hydration*, and is very important in weathering. An important effect is the increase of the volume of the mineral acted upon. The operation of hydration and oxidation is well illustrated in the

weathering of iron pyrite (FeS_2) which frequently occurs disseminated through rocks. The first, and usually most conspicuous effect is the appearance of a yellow stain on the rock. If the pyrite is abundant, hydration may cause the rock to fall to pieces as a result of the increase of volume and of the formation of sulphuric acid. Building stones which are uniform in color when first quarried sometimes become discolored, after an exposure of a year or more, by blotches of brown stain. Upon examination, it is usually found that the stain was formed from the weathering of small crystals of pyrite. From these blotches the stain spreads, sometimes covering an area of 100 or more square inches.

4. **Carbonation.** — By the union of carbon dioxide, derived from the air and soil, with the calcium, magnesium, or iron of complex silicates, soluble compounds are formed which upon being carried away in solution cause the rock to crumble. This is an important cause of the disintegration of granite, although oxidation and hydration are also effective in the same process. If organic acids derived from decaying vegetable matter are present in water, they tend to decolorize red and yellow rocks. Such decolorization can often be seen where water trickles over cliffs. For example, the red cliffs of the Vermilion River in northern Ohio are bleached wherever rivulets trickle over them. This is accomplished by the union of the carbon dioxide with the oxides of iron which gave the red and yellow color to the rock.

5. **Organisms.** — Although not agents of the weather, the chemical action of plants and animals should be considered in a discussion of rock disintegration. Certain bacteria are found in great numbers on the surface of bare rock. They live not only in low, moist regions, but even on mountain peaks, where they have been found coating the surfaces and crevices of the rocks. They draw their nourishment from the nitrogen and other compounds brought down in snow and rain. Rocks are attacked by the nitric acid which these bacteria form from the ammonia of the air and water. The chemical action of their excretions makes them an important though inconspicuous agent of disintegration. Other organisms, such as lichens, mosses, and flowering plants, contribute to the decomposition of rocks. The roots of trees not only pry the rocks apart (p. 33), but they also act chemically by producing carbon dioxide and organic acids, which dissolve the lime and transform the silicates into carbonates and other products.

Comparison of Effects of Chemical and Mechanical Weathering. — Chemical decomposition of rocks is slow and long continued as compared with mechanical disintegration, which is a rapid process. By the former the rocks are broken up into fine particles, and by the latter into larger and smaller fragments. Chemical action is not only long continued, but is also more universal than mechanical action, being important under all climates, except in desert regions and on mountains where mechanical disintegration is so rapid that sufficient time is not permitted for conspicuous chemical action. Chemical decomposition tends to smooth surfaces, while mechanical disintegration tends to roughen them. Where the mechanical predominates, the slopes are stronger and tend to form cliffs.

RESULTS OF WEATHERING

Some of the most conspicuous features of scenery are produced by weathering. These features are seldom due to a single agent, but more often to two or more acting in conjunction.

FIG. 13. — Pinnacle Peak, Canadian Rockies. The ragged outlines are due largely to frost work. (Photo. M. H. Smith.)

The rough and jagged peaks so characteristic of high mountains have been sculptured largely (1) by frost and (2) by changes in daily temperature (p. 31) (Fig. 13). The débris derived from such peaks may accumulate in the valleys and on the sides of the mountains to great depths, in some cases more than a thousand feet. Where the supply of talus is too great for the stream in the valley to remove, the stream is dammed and a lake is formed (Fig. 14). The form of the crests and cliffs of high mountains is determined to a large degree by cracks which have a uniform direction (joints), as, when the water which fills them freezes, the rock is broken off along these planes. In tropical regions the fractures of the rock are also important, since they permit the access of water, and chemical decomposition is therefore accomplished at greater depths at these points.

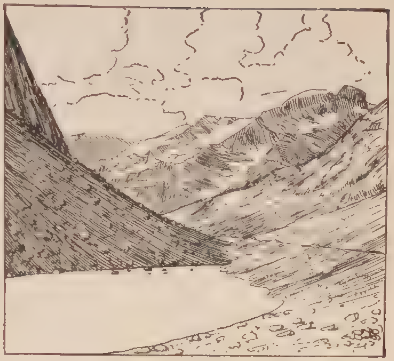


Fig. 14. — Drawing showing a stream so dammed by talus as to form a lake. Note the angle of the talus slope.

It is often possible to state from the shape of the topography in any one locality what the nature of the underlying rock is, but a general rule is impossible, since the same rock is differently affected by the weather under different climates. For example, granite rocks which in a cold climate may be broken into jagged crests, may, in moist, tropical regions, be reduced to rounded forms through the chemical agencies.

Spheroidal Weathering. — Spheroidal weathering results from chemical action and should be distinguished from similar shapes which are produced by exfoliation due to changes in daily temperature (p. 31). When water percolates through the joints (p. 258) and horizontal planes into which all rocks are more or less divided, it attacks with its dissolved gases all the rock surfaces with which it comes in contact; but since the corners and edges of the blocks formed by these joints and planes have a greater

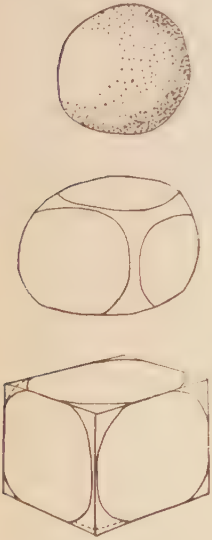


Fig. 15. — Diagrams showing the effect of weathering upon rock cut into angular blocks by joints (see Figs. 1, 2). The corners and edges are most affected, and the blocks tend to become spheroidal. (Modified after Hobbs.)

surface exposed, they are more vigorously acted upon. Such places, too, encounter water from two or more directions and are more likely to be affected by the strongest solutions. The greater weathering of the edges, and especially of the corners, causes them to disintegrate more rapidly, leaving a spheroidal core of unweathered rock, embedded in less compact, weathered rock. When the rock is exposed to the action of wind and water, the unaltered, spheroidal core is exposed (Figs. 15, 16).

FIG. 16. — Granite weathering under tropical conditions. Rhodes' Grave, southern Rhodesia. The bowlders are residual fragments of a sheet of granite that once overlay the hill. (Photo. G. A. J. Cole.)

Differential Weathering. — When rocks are not uniform in character but are softer or more soluble in some places than in others, an uneven surface may be developed (Figs. 17, 18, 19); in deserts by the action of the wind and in moist regions by solution. Columns of rock which have been isolated in any way show the effect of *differential weathering.* In arid regions the lower parts of the columns (Fig. 20) are worn away more rapidly than the upper parts, because the drifting sand is more abundant and effective near the ground, and the bases grow smaller and smaller until the monuments finally topple over.

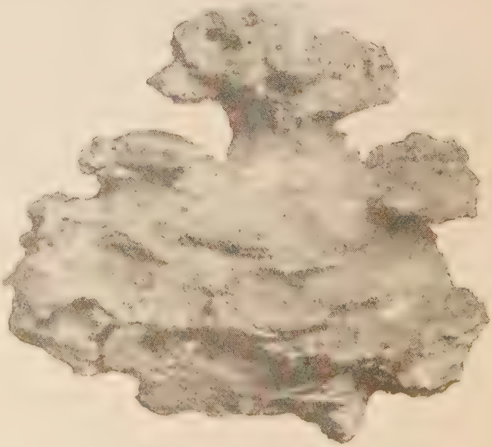


FIG. 17. — A bowlder showing differential weathering. The projecting portions are relatively insoluble silica, while the main portion is limestone.

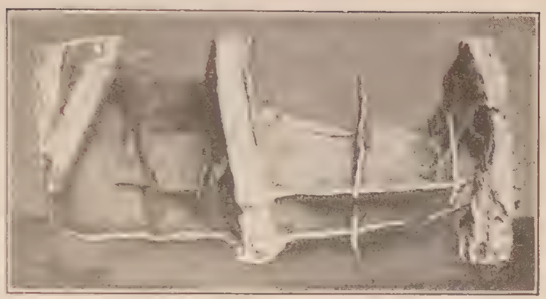


FIG. 18. — Differential weathering. The limestone has been dissolved, leaving the quartz veins projecting.

Widening of Valleys. — Valleys are widened by the work of streams (p. 81), but a large part of the width of their upper portions is due to the work of the weather, which first disintegrates the rocks, after which rain, hillside creep (p. 31), and other agents bring the weathered material within reach of the stream which carries it away.

Rock Mantle and Soil. — We have seen that everywhere on the earth's surface the rock is being broken to pieces by one or more of the agents of weathering. This results in the accumulation of a mantle of rock waste which in the process of time would cover the lands to a great depth if it were not removed. The thickness of the *mantle rock* varies greatly. In tropical regions the solid rock may not be encountered even at a depth of 150 feet, and in Washington, D.C., granite can be excavated with pick and shovel at a depth of 80 feet. In the Valley of Virginia and in the Blue Grass regions of Kentucky a thick layer of soil, representing the insoluble portion of many feet of limestone, covers the underlying rock. Under normal conditions (Fig. 21) the soil is thickest on the crests and at the bases of hills, and thinnest on the

FIG. 19. — The more rapid weathering of a weak bed of limestone in the cliff has formed the shelf. Helderberg Mountains, near Albany, New York.

slopes, since loose material has a tendency to creep down hill (p. 31). In regions which have been covered by glaciers (p. 168) the soil has often been removed from the hilltops by them.

FIG. 20. — An erosion pillar, shaped largely by the work of wind-blown sand. Near Adamana, Arizona.

The same agencies that cause the disintegration of the rock break up the mantle rock to finer and finer particles and form *soil.* Soil grades into the coarser *subsoil* which has not yet been completely disintegrated. This subsoil is gradually brought to the surface by earthworms where the soil is clay, and by ants where it is sandy. In the aggregate, the work of these animals is important. It has been estimated that in England earthworms bring 17 to 18 tons of material an acre to the surface each year, and that in Massachusetts ants bring up one fourth inch of earth. Leaves and other organic matter which are carried into the soil and subsoil by earthworms form organic acids which hasten the chemical decomposition of the rock. Roots of plants and overturned trees also help to mingle soil and subsoil. The fertility of soil is greatly increased by the organic matter, either animal or vegetable, which it contains, but its character depends largely upon the rock from which it was derived.

FIG. 21. — Diagram showing the relation of residual soil to underlying rock. (U. S. Geol. Surv.)

Kinds of Soil. — Mantle rock and soil are moved by hillside creep (p. 31), by rain (p. 33), by avalanches, by landslides (p. 73), by slumping (p. 73), etc.; all of which combine to remove it from the uplands and carry it to the valleys. There are two kinds of soil, (1) *residual soil*, that derived from the rock which it covers, such as that which overlies large areas where the country has not been affected by glaciation, and (2) *transported soil.* Transported soils may be further classified as (*a*) alluvial, those which have been carried and deposited by streams, and which vary greatly in composition from the finest clay to coarse gravel; (*b*) glacial soils which in any place may vary greatly, both in the character and the size of their constituents (p. 663); (*c*) soils of sand and clay deposited by the winds, such as the fertile loess of China (p. 53) and of the western part of the United States, and (*d*) talus soils of mountain regions.

Removal of Soil. — When, by deforestation, overgrazing by animals, or other causes, the vegetation which prevented the washing of the soil is removed, the soil may be carried away rapidly, and a fertile region may become almost a desert. This appears to have been true of portions of China and Greece. When the fertile soil is once removed, it is difficult for plants ever again to gain a foothold, and the region may be permanently desolated. It is stated that a single lumberman may in fifty years deprive the human race of soil that required tens of thousands of years to form.

REFERENCES FOR WEATHERING

Buckley, E. R., — *Building and Ornamental Stones:* Bull. Wis. Geol. and Nat. Hist. Surv. No. 4, 1899, pp. 11–34.
Dana, J. D., — *Manual of Geology,* pp. 118–129; 158–159.
De Martonne, E., — *Géographie Physique,* 1909, pp. 404–411.
Geikie, A., — *Textbook of Geology,* 4th ed., Vol. 1, pp. 447–465.
Haug, E., — *Traité de Géologie,* 1911, pp. 371–401.
Merrill, G. P., — *Rocks, Rock-Weathering and Soils,* pp. 173–285.
Shaler, N. S., — *Aspects of the Earth,* pp. 300–339.

CHAPTER II

WORK OF THE WIND

THE conditions essential for the effective work of the wind are aridity and a scarcity of vegetation. Since such conditions prevail over more than one fifth of the land surface of the world, the work accomplished by this agent is of great importance.

WIND AND SAND

Wind without Sand. — Wind is much less effective without sand than with it, but is nevertheless important. In semiarid regions and in those which are suffering from a long period of drought, cultivated fields may be excavated disastrously. In Wisconsin there are extensive regions of light lands which almost every year suffer from the drifting action of the wind. In these regions winds dry up the soil and sometimes sweep away the crops of grain, even after they are four inches high, uncovering the roots by the removal of one to three inches of surface soil. (King.) During the drought of 1894 in Nebraska, the finely pulverized soil of the cultivated fields was blown out over extensive areas to a depth of two or more inches and was piled up in small dunes near fences and buildings. *Blow-outs*, as the pits excavated by the wind are called, are often the indirect result of the close grazing of a light soil, or are developed in land which is covered with a sparse vegetation. Blow-outs may be excavated to a depth of ten feet or more, and at certain seasons of the year may be occupied by temporary lakes. The work of the wind in removing loose sand is termed *deflation.*

Besides these more important effects of the wind, rocks are dislodged from cliffs by its force, as in the Orkney and Shetland Islands, where it is common to find pieces of flagstone or slate weighing several pounds, which have been detached from the precipices and blown upon the moors above during high gales. (A. Geikie.) Trees are blown down; water is thrown into waves; and birds, insects, and seeds are carried about.

Wind with Sand. — As soon as the wind picks up pieces of the mantle rock it has tools with which to work, and it becomes a geological agent whose effect in desert regions is not easily overstated. It is from the mantle of rock waste formed by the agents of the weather, and from the sediment carried to the deserts by the mountain streams that the sheets of sand which cover the deserts are made. The work of wind laden with sand is well illustrated in the artificial sand blast by which granite is ground and glass is etched in desired patterns. Telegraph poles in arid regions have been cut off near the base by wind-blown sand.

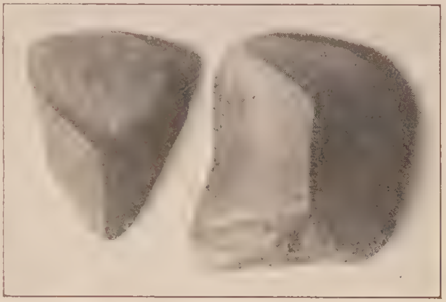


Fig. 22. — Pebbles faceted by the abrasion of wind-blown sand (*dreikanter*).

Pebbles worn by the wind (Fig. 22) usually have a characteristic, brazil-nut shape (*dreikanter*), the faces meeting in ridges.

Fig. 23. — Surface eroded by wind-blown sand. The small table is the remnant of a once extensive bed. (De Martonne.) (See Fig 24.)

This shape is explained as follows: the planing of the exposed surface of the pebble by the wind-blown sand continues until the pebble stands on a narrow base. It is then overturned by a slightly stronger gust of wind and a new surface is exposed which is, in turn, planed by the blown sand. The pebble may be turned over by the undermining of the sand on one side, when the pebble falls into the depression thus made, and the wind is permitted to plane another surface. Pebbles of this sort are sometimes found in ancient rocks and afford evidence of the physical conditions of the time in which they were deposited.

Wind scour wears away the softer strata of a desert much more rapidly than the harder, producing wide plains above which the harder rocks stand as isolated hills. In areas composed of horizontal strata the soft rocks are removed, and the region is lowered to a harder stratum, which may, in turn, be cut up and the whole region reduced to a still lower level. During this gradual lowering, the deserts are eroded, leaving extensive, flat-topped elevations capped by harder rock (Figs. 23, 24), which are later cut up into conical hills and finally destroyed.

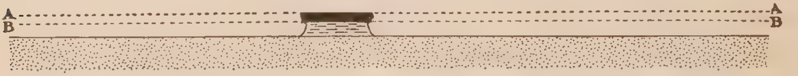


FIG. 24. — Diagram showing a table such as that appearing in Figure 23, formed by the wearing away of the beds *A* and *B*, by wind-blown sand.

In desert regions where plains predominate, we sometimes find mountains whose bases are covered for 1000 to 2000 feet with sand, rising above the plains. (McMahon.) In places we find also bare rock exposed in the basins, showing that the wind is able to excavate the rock to low levels. In fact, it seems probable that so long as the ocean is held back from a desert, eolian excavation may go below sea level. The limit to eolian excavation is the level of underground water (p. 56), for when that is encountered, wind erosion is ineffective, since the sand is then held by the moisture and further removal prevented.

Sand Dunes. — When wind meets an obstacle, its velocity is lessened and, if it carries sand, some of its burden is dropped. The mounds of sand which are thus piled up by the wind are called *dunes*. Sand dunes are most abundant (1) in deserts, being as a rule more numerous in low-lying areas; (2) on sandy coasts where the prevailing winds are on shore; and (3) near the beds of rivers whose volume varies, leaving broad areas of sand exposed during the dry season. Dunes of this origin are common in Nebraska, Kansas, Mexico, and many other regions. Sand dunes occur in the above-mentioned regions because there only the wind finds sufficiently thick accumulations of dry sand and sufficiently extended flat surfaces for effective work. There also the winds blow in the same direction a sufficient length of time. Frequent changes in the direction of winds are as unfavorable to the development of dunes as vegetation or a rough topography.

If the direction of the wind is constant, typical dunes will have a gentle slope on the windward side and a steep slope on the leeward side (Fig. 25). This difference between the windward and leeward slopes is due to the fact that the sand is pushed up the former by the wind and dropped over the crest, where it comes to rest at a steeper angle. On the other hand, if the prevailing direction of the wind changes from season to season, the difference between the angles of the slopes will be less marked. The slope is generally steepest on high dunes, but is never greater than 10° on the windward and 34° on the opposite side. Since the winds vary greatly in velocity from time to time, the size of the sand particles carried up the dunes differs and usually produces distinct layers, or stratification. The inclination or dip (p. 252) of the stratification also varies widely in direction and steepness (Fig. 26), since it depends upon the direction and the force of the wind. The formation of this *cross-bedding*, as the layers in one

FIG. 25. — Sand dunes. The direction of the wind was from the right to the left. (Photo. D. T. MacDougal.)

deposit which vary in direction are called, is clear when the conditions of their formation are considered. If the direction and force of the wind remain constant, the sand will be carried up the gentle slope and will fall over the steep slope, forming layers of uniform inclination. If, however, as is nearly always the case, the force and direction of the wind vary, the sand will be laid down on different sides of the dune at different times. In either case cross-bedding will be produced, but it will be more irregular in the second case than in the first.

FIG. 26. — A quarry in eolian limestone, Bermuda Islands. The cross-bedding was formed by the shifting winds which carried the sand.

Shape and Origin of Dunes. — Where winds are moderate and the supply of sand is small, crescent-shaped dunes (Fig. 27 *A*) are formed; if the wind is moderate but the supply of sand great, dune ridges are often developed which are at right angles to the direction of the wind (Fig. 27 *B*); while in regions where the prevailing winds are strong and the sands abundant, long ridges parallel to the direction of the wind usually result (Fig. 27 *C*). The crescent shape of dunes results when wind, blowing over a sandy stretch, heaps the sand into small piles. The grains of sand which are subsequently carried to the piles are deviated to the right and left, until crescents are formed. When the direction of the wind changes, the points of the crescents disappear and then form on the lee side in a new direction.

Any obstacle, such as a bush, a rock, a fence, or even a mere roughness of the land surface, may cause the beginning of a dune. Dunes are also sometimes formed when the sand is wet by seepage. These moist heaps serve to anchor additional particles of sand until a mound some feet in height is formed, which may afford lodgment for shrubs. The presence of obstacles is, however, not always essential to the formation of dunes. This can be observed on a small scale on a smooth asphalt street, where the dust is seen to be collected into small ridges, perpendicular to the direction of the wind. The waves of the sea have the same origin as these ridges, but the molecules of the water are not carried along by the wind as are the grains of sand, but after completing their orbits (p. 199), return to their original positions.

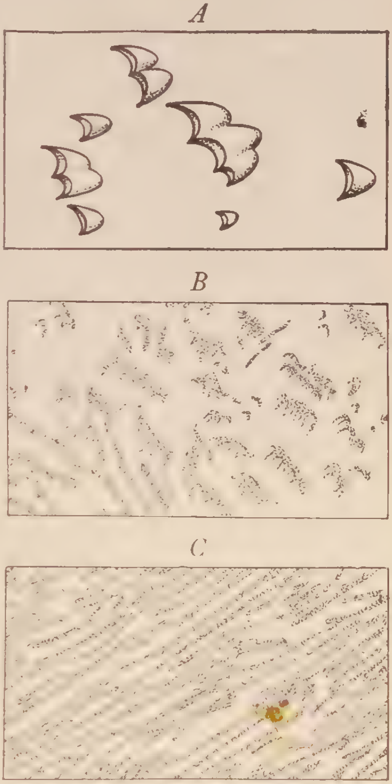


Fig. 27. — Diagrams showing the form of sand dunes. In *A* the wind blows from the upper right-hand corner. The supply of sand and strength of wind are moderate. In *B* the direction of the wind is from the upper right-hand corner. The supply of sand is large and the winds moderate. Under these conditions dunes transverse to the wind are formed. When the supply of sand (*C*) is large and the winds strong, dune ridges parallel to the direction of the wind are formed.

Migration of Sand Dunes. — Dunes are constantly migrating unless the sand of which they are composed is prevented from blowing by grass or other vegetation (Fig. 28). The forward movement is accomplished by the force of the wind, which shifts the sand of the dunes to the leeward. This can be seen on a windy day, when the crests of the dunes appear to smoke. The rate at which dunes move varies, depending largely upon the velocity of the wind and the height of the dune, small dunes migrating the faster. In Denmark the rate is from three to twenty feet a year; in France, on the Bay of Biscay, the sands have advanced at a rate estimated from 15 to 105 feet a year, burying in their progress forests, farms, vineyards, villages, and churches (Fig. 29). Some of these, after being buried for years, have been again uncovered by the further advance of the dunes. The church of Legé, taken down at the end of the seventeenth century and rebuilt two and a half miles inland, had again to be removed 160 years afterwards, showing an advance of the sands at a rate of 81 feet a year. (Wheeler.) On the south side of Lake Michigan forests which were covered by sand dunes have been uncovered as the dunes moved on. There are hundreds, perhaps thousands, of square miles of buried towns and cities in Central Asia.

One of the difficulties in connection with the maintenance of the Suez Canal is the sand which is constantly being blown into it from the desert, necessitating frequent dredging. Many communities in the past which depended for their existence upon irrigation have been obliged to abandon their homes, because an unstable government failed to keep the irrigation canals free from drifting sand.

FIG. 28. — Dunes held by mesquite bushes. (Photo. D. T. MacDougal.)

The drifting of sand has often affected the drainage of the land; the Grand Calumet River (Fig. 30) formerly emptied into Lake Michigan in Indiana, but its mouth became so filled with drifting sand that the course of the stream was reversed and it now empties into the lake at Chicago, twenty-four miles distant. Large lakes have been formed in consequence of the damming of rivers by dunes, where they emptied into the sea. One such in France, Lake Cazaux, has a width of nearly seven miles and a depth of 130 feet.

FIG. 29. — A sand dune covering a cabin. The origin of the sand is the seabeach. (Bermuda Islands.)

The ripples which mark the surfaces of sand dunes shift their positions gradually and, in general, are affected as are the dunes.

The movement of sand dunes can sometimes be prevented by plant-ing grasses, shrubs, and trees on the gentle slopes in order that they may hold the sand with their roots. This has been done successfully in San Francisco, in Provincetown (Massachusetts), and elsewhere.

Beneficial Effect of Dunes. — Dunes are not, however, always a detriment to man. A writer states that the people of Holland and Denmark "deal as carefully with their dunes as if dealing with eggs, and talk of their fringe of sand hills as if it were a border set with pearls. They regard these as their best defense against the sea." (Kahl.) As this implies, Holland depends to a large degree for its protection from the sea upon sand dunes, which are from one to three miles wide and from 40 to 50 feet high. The sand of certain dunes in England (Padstow), which consists largely of shell fragments, is used to some extent for a fertilizer.

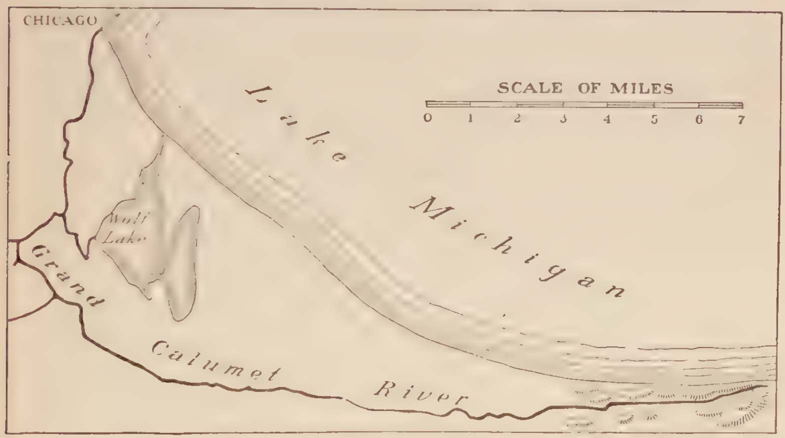


FIG. 30. — Map of the Grand Calumet River. The river formerly entered Lake Michigan at the east, but was cut off by sand dunes and now enters the lake at Chicago.

Material of Dunes. — The material of sand dunes varies but is usually quartz sand. However, in the Bermudas, Bahamas, and portions of England, dunes are composed of shell sand ($CaCO_3$). In the Bermudas these sands are cemented by the rain water which dissolves the calcium carbonate and later redeposits it, thus forming stratified eolian rock. When the shallow, alkaline lakes of portions of New Mexico (Otero Basin) dry up, they leave on their beds thin sheets of various salts, chiefly gypsum. These soon curl up into leaves which, when blown together, are broken into gypsum and salt sands. The winds carry the light gypsum out to the plains, where it gathers in a great series of white dunes, 60 to 100 feet in height, covering an area 15 miles by 40 miles in extent. Dunes are formed also of fine clay, as well as of disintegrated granite sand.

Height of Dunes. — The height of dunes in regions where the direction of the wind is fairly constant is seldom more than 300 feet, but in such deserts as the Sahara, where the wind varies from season to season, the height may reach 1500 feet. In the latter case, the dunes do not migrate, and their greater height is due to the piling up of the sand from different directions.

Eolian Sandstone. — Extensive strata of sandstone of very ancient date are known to have been formed of wind-blown sand. Rocks of this origin can often be distinguished from the sandstones laid down on the ocean bottom. The following differences assist in recognizing the source of the original deposits. (1) The former consist chiefly of quartz, the softer minerals having been worn to dust and carried away, while in the latter the softer and harder minerals are more likely to occur together. (2) Since water-laid sands are carried in suspension, they are subjected to less wear than eolian sands, as the water between the particles acts as a cushion, and the grains are consequently less worn and more angular than the sand grains which have been buffeted by the winds. (3) The stratification of eolian sand (Fig. 26, p. 48) usually exhibits *cross* or *false bedding* (p. 47), *i.e.*, it is not horizontal but varies greatly in inclination and direction within short distances. (4) Wind-blown sands may also be distinguished from marine sandstones by the character of the fossils, if such exist.

Dust. — As sand grains are borne to and fro by the wind, striking against each other or against rock surfaces, the softer grains are reduced to dust, and even the harder ones may finally reach a similar state. The dust thus formed is carried by air currents, often to great distances. In a single storm in 1901 it is estimated that 1,960,420 tons of dust were carried from the Sahara desert to Europe, reaching Italy on the second day of the storm, and Germany and Denmark on the fifth day. It is probable that every square mile of the earth's surface has dust upon it from every other square mile. Even the snows of mountain glaciers and those of the Arctic and Antarctic regions contain dust, carried to them from lands hundreds of miles away.

Loess. — One striking result of the transportation of dust by winds is that regions to the leeward of deserts are constantly receiving dust which settles gradually upon them. Such a deposit of fine dust is called *loess*. The fine dust is carried by the wind to the edge of the dry region, where it is precipitated by rain or falls slowly by its own weight. Here some of it is held by the grasses of the high plains, whose roots have left, upon their decay, the vertical columns characteristic of loess. "But if the desert dust has ceased to be the plaything of the wind, it has not ended its journey. From now on rills take charge of it and continue the work of which the wind is no longer capable." (De Martonne.) In this way loess is spread over a large territory.

FIG. 31. — Loess deposits, Shan-si, China. The canyon-like depression was excavated by the wind as the loess was loosened by traffic. The two levels on the right are old roads. The ability of loess to stand in almost vertical walls is shown. (Carnegie Institution.)

In China there are extensive areas which have been built up by the accumulation of such dust, in some regions to a depth of 1000 to 2000 feet. The fertility of the soil of these regions is remarkable. Although cultivated for many thousands of years without artificial fertilizer, it still retains its fertility. This is due largely to the constant supply of new dust from the desert. It is stated that the limit of the loess practically marks the extreme limit of the extension of Chinese agriculture and commerce. (Richthofen.) Large areas in the United States (p. 657) and in Argentina are also covered with loess, and in all such regions grass and grains flourish, although trees are usually few. The principal deposits of loess in the United States were derived from the fine material of glacial deposits which were caught up by the winds during the dry phases of the interglacial periods (p. 657).

Loess has the property of maintaining a vertical face when cut through artificially or by streams. In China the roads of the loess region are often in nearly vertical, walled canyons (Fig. 31), many feet below the surface, having been deepened by the blowing out of the dust of the traveled road. On either side of these roads cave houses have been excavated and furnish homes for many thousands of people.

Dust is obtained by the winds from sources other than desert sand, such as fine volcanic ash, solid particles of smoke, pollen of flowers, and spores of plants. The amount of material thrown into the air during volcanic eruptions is enormous. The volcano Krakatao in the East Indies, for example, in 1883 threw volcanic dust to a height of several miles, which in fifteen days had encircled the globe. So abundant was the dust in the air that for many months after the eruption the sunsets were remarkably brilliant. In Kansas and Nebraska there are deposits of volcanic dust, locally 30 feet thick, which had their source in ancient volcanoes hundreds of miles away.

REFERENCES FOR THE WORK OF THE WIND

Beadnell, H. J. L., — *Sand Dunes of the Libyan Desert:* Geog. Jour., Vol. 35, 1910, pp. 379–395.

Cobb, C., — *Where the Wind Does the Work :* Nat. Geog. Mag., Vol. 17, 1906, pp. 310–317.

Davis, W. M., — *The Geographical Cycle in an Arid Climate:* Jour. Geol., Vol. 13, 1905, pp. 381–407.

De Martonne, E., — *Géographie Physique*, 1909, pp. 649–672.

Free, E. E., — *The Movement of Soil Material by Wind:* Bull. U. S. Bureau of Soils, No. 68, 1911.

Geikie, J., — *Earth Sculpture*, 1898, pp. 250–265.

Haug, E., — *Traité de Géologie*, 1911, pp. 387–403.

Hobbs, W. H., — *Earth Features and their Meaning*, 1912, pp. 197–222.

Huntington, Ellsworth, — *The Pulse of Asia*, 1907.

Keyes, C. R., — *Relation of Present Profiles and Geologic Structures in Desert Ranges:* Bull. Geol. Soc. America, Vol. 21, 1910, pp. 543–563. (Dr. Keyes holds extreme views on wind erosion.)

MacDougal, D. T., — *The Desert Basins of the Colorado Delta:* Bull. Am. Geog. Soc., Vol. 39, 1907, pp. 705–729.

Walther, J., — *Das Gesetz der Wüstenbildung*, 1900.

Topographic Map Sheets, U. S. Geological Survey, Illustrating Wind Work

Moses Lake, Washington.
Larned, Kansas.
Kinsley, Kansas.
Pratt, Kansas.
St. Paul, Nebraska.
Camp Clark, Nebraska.
Norfolk, Virginia — North Carolina.
Sandy Hook, New Jersey — New York.
Toleston, Indiana.
Yuma, California — Arizona.

next

CHAPTER III

THE WORK OF GROUND WATER

TAKING the world as a whole, about 78 per cent. of the rainfall either soaks into the ground or is evaporated, the remainder — the run-off — being carried directly into streams and rivers. The amount of the precipitation which is retained in the soil depends upon (1) the climate, (2) the slope of the ground, (3) the porosity of the soil and rock, and (4) the amount and character of the vegetation. In moist climates the run-off may amount to as much as one half of the rainfall, while in arid regions, on account of the excessive evaporation and the dryness of the soil, there may be no run-off. That portion of the rainfall which sinks into the soil is called *ground water*. Once beneath the surface, it continues its descent through the pores and cracks of the rock until it may reach great depths.

Quantity of Ground Water. — All rocks are more or less porous, even granites contain some water; for example, chalk may hold two gallons of water a cubic foot, and sandstones may hold 20 to 30 per cent. of their weight. The total amount of water in the rocks is therefore very large, and it is probable that, if the ground water were squeezed from the rocks, there would be enough to cover the earth with a sheet of fresh water one hundred or more feet deep. Locally, the quantity of underground water may be much greater; as, for example, in Wisconsin and Minnesota, where the underlying sandstone alone contains enough water to form a layer 50 to 100 feet deep. The ground water of any region is not always derived from the local rainfall, but may have had a long subterranean course, as is true of the underground water of the Great Plains, the source of which is in the mountains, many miles distant.

The Water Table. — The level beneath which the rock is saturated with water is called the *water table* or the *level of underground water*.[1] This varies greatly in different regions. In humid portions of North America it is from one to forty feet below the surface; in limestone regions, where the drainage is largely subterranean, such as in portions of Kentucky and Tennessee, it may be two to three hundred

---

[1] "In deep mines in various parts of the world water is found only in the upper levels, within 2500 feet or less of the surface, while below that the mines are dry or even dusty." (Scott.)

feet deep; while in the Colorado Plateau, where the surface is cut by deep canyons, it is sometimes 3500 feet beneath the surface; or it may be entirely absent, except where water-bearing strata conduct water from other areas. In the Navaho Reservation in Arizona, for example, no water except artesian (p. 59) is encountered below a depth of 100 feet. (H. E. Gregory.)

The water table varies with the slope of the land, being farther from the surface on the hills than in the valleys (Fig. 32). The greater depth beneath the surface of the hills is due to gravity, which between rains and during dry seasons tends to pull the water downward to the level of the valleys, but is unable entirely to do so because of capillarity and friction of the water with the grains of rock. As a result, the water table is never flat in a hilly region, although it is more nearly so after a prolonged drought. It necessarily follows that the depth of the water table in any place will depend largely upon (1) the slope of the land, (2) the porosity of the rock, and (3) the frequency and character of the precipitation, slow, soaking rains accomplishing more than sudden and brief downpours.

In forested areas it is found that the water table is lower than under similar conditions of moisture, rock, and topography in other regions, because of the great quantity of water abstracted by the roots of the trees and lost by evaporation through the leaves. The headwaters of streams, however, should be kept forested, since much of the water of excessive rains is retained in the thick layer of forest mold, from which it slowly drains away and thus tends to prevent great floods.

Wells. — When wells are sunk, it is necessary that they penetrate to a permeable rock or to a much fractured one (Fig. 33) below

FIG. 32. — Diagram showing the water table or level of underground water *A A A A* and the effect upon natural and artificial depressions.

the water table (Fig. 32), for otherwise they do not afford a perennial supply of water. The value of wells, both for drinking purposes and for irrigation, is inestimable. It is stated that in India more land is irrigated from wells than from streams, and in southern California one half of the irrigation water and the greater part of the city supplies are drawn from the sands and gravels that underlie the valleys. It is estimated that 75 per cent. of the population of the United States depends for its water supply directly upon underground water.

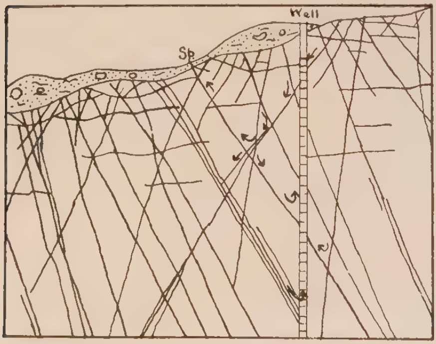


Fig. 33. — Diagram showing the source of well and spring water in fractured rock. (Modified after H. E. Gregory.)

Movement of Ground Water. — Underground water seldom moves in definite channels, except in limestone regions, but percolates slowly through the pores and crevices of the rocks. Even in coarse sandstone the rate of movement may be only one fifth of a mile a year, although in regions of soluble limestone it may flow several miles a day in tunnels. In such regions the direction of the underground flow may be opposite to that of the surface streams, since it is determined by the dip of the rock.

Much of the ground water eventually reaches the surface again unless it enters into chemical combination with minerals of the rocks with which it comes in contact. A large amount is taken up by plants and passes into the atmosphere by evaporation; some of it is drawn out in wells; some seeps out, or is discharged in springs, either in river valleys or in lakes and seas. Large springs of fresh water come to the surface of the Mediterranean, the Gulf of Mexico, and other seas at short distances from the shore, and in certain places fresh water is obtained from springs on the ocean bottom by diving.

The total quantity of mineral matter dissolved by the ground water is enormous. The greater part of the 4,975,000,000 tons of mineral matter carried to the ocean each year was obtained by the streams from the ground water which escaped through springs and seepage.

Depth of Ground Water. — We have seen that the rocks of the earth's surface are much broken by cracks of various kinds. This condition holds true of rocks below the earth's surface, down to a depth where the weight above them is greater than their strength to resist pressure. This outer zone is called the *zone of fracture*. The depth of this zone varies with the strength of the rock. In the case of soft rocks, such as shales, no crack may be found at a depth of 2000 feet, while in the strongest rocks some cracks may possibly exist "at a depth of at least eleven miles." (Adams.) At depths greater than eleven miles it does not seem possible that a crevice can open, and if a fracture should occur, the parts would actually weld together. It is evident from the above that water will not descend a greater distance than eleven or twelve miles under the most favorable conditions, and usually far less than that. The temperature of the rocks, and therefore of underground water, increases 1° F. for each 60 to 100 feet of descent, a fact which accounts for the warmth of deep wells and springs coming from great depths (p. 273).

Artesian Wells. — Strictly speaking, an artesian well is one in which the water rises above the surface of the ground as a fountain, but the term is now, unfortunately, frequently employed for any deep well from which water is obtained, whether it flows to the surface or not. This change in usage is doubtless due to the fact that often artesian wells, after flowing for some months or years, cease to do so and must be pumped because of the excessive withdrawal of water from the artesian basin. This was true of the first artesian well at Artois, France (from which the name "artesian" was derived). Many wells in the San Bernardino valley, California, which flowed strongly when first drilled, are now pumped. The conditions favoring artesian water (Fig. 34) are (1) a porous bed capable of absorbing and transmitting large quantities of water; (2) relatively impervious beds above and below; (3) exposure of the porous stratum where it may absorb water supplied either by rain or by streams flowing over it; (4) an inclination of the water-bearing stratum so that gravity may force the water down; (5) a lack of easy escape of the water at lower points; and (6) a sufficient supply of water to maintain the "artesian head." The artesian water of South Dakota (Fig. 35), for example, is derived from a saturated sandstone bed which receives its water in the Black

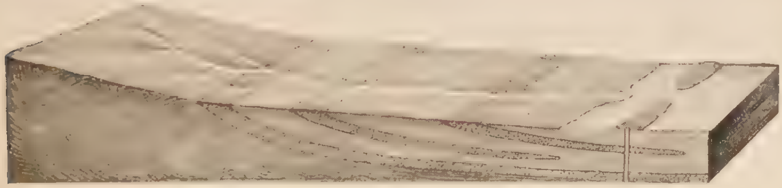


FIG. 34. — Block diagram showing the conditions favorable for artesian water. The porous beds (dotted) receive water from the rain which falls on their outcrops, and from the streams which lose somewhat in volume as they flow over them. Three water-bearing beds (aquifers) are shown, from two of which water can be obtained on the barrier island which is separated from the mainland by a salt-water lagoon.

Hills from the rain that falls on it and the streams that flow over it. It is covered by clays and shales as it extends eastward, and when borings are made at elevations lower than its source in the Black Hills, the water rises and supplies wells even 350 miles from this source.

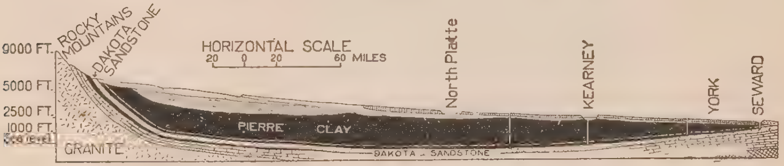


Fig. 35. — Diagram showing the conditions favorable for artesian water, from the Rocky Mountains to eastern Nebraska. The Dakota sandstone under the impervious Pierre clay carries water from the Rocky Mountains and supplies artesian wells on the plains. (U. S. Geol. Surv.)

Artesian wells vary in depth, some being 7000 feet deep, while others may be less than 100 feet. Artesian water, both for drinking purposes and for irrigation, is of great importance. It varies greatly in composition, some wells affording excellent water, while others may be so charged with salts as to be useless for drinking or irrigation.

Springs corresponding to artesian wells are formed if the impervious bed overlying the porous bed is broken by a fissure or fault (p. 25). These springs may be of great volume.

Chemical Work of Ground Water. — (1) *Solution.* Pure water has little power to dissolve the minerals of which rocks are composed, but rain water is seldom pure since it receives carbon dioxide from the air, and, in passing through the soil, takes up this and other acids formed by the decay of organic matter. It may be heated in its downward course and is subjected to great pressure. Thus equipped, its solvent power is greatly increased, and in its descent through the rocks it carries away the more soluble minerals and the cement of many of the rocks, rendering them more porous and causing their decay. At or near the surface, water is an active agent in causing the disintegration of the rocks, both by the mechanical work of the frost and by its chemical action.

(2) *Replacement and* (3) *Deposition.* — When ground water contains much mineral matter, a slight change in temperature or pressure, or a mingling with other waters of a slightly different composition, may cause the dissolved material to be deposited. This results in *replacement*, and *deposition in cavities.* (2) Replacement results when in its descent ground water dissolves and carries away one mineral, deposit-

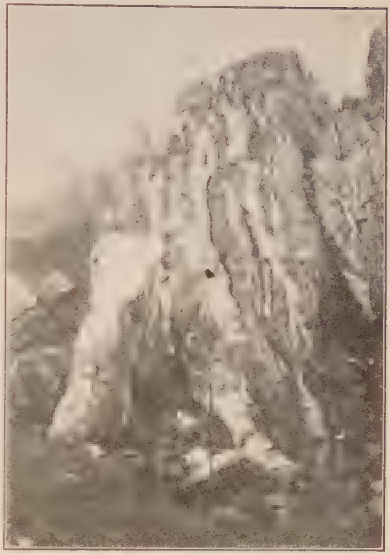


FIG. 36. — Quartz veins (white) in limestone, near Williamstown, Massachusetts.

ing another in its place. Shells, bones, and trees are petrified by the replacement, molecule by molecule, of the original substance by mineral matter. (3) Deposition occurs when minerals are taken from the rock in one place and later deposited elsewhere. In this way many metallic and other veins (Fig. 36) are formed (p. 371), and loose sands and clays are cemented into hard rocks. Besides this more important work, concretions (p. 75) and geodes (p. 78) are formed, and in regions of thick limestone cave deposits are built up (p. 70).

Belts of Weathering and Cementation. — The *belt of weathering* extends from the surface of the ground to the level of underground water and is of variable thickness. In this belt the greatest chemical decomposition of rocks occurs. This work consists mainly in hydration, oxidation, absorption of carbon dioxide, and solution, and it is here that minerals with complex molecules are broken down into simpler compounds. This belt is, therefore, that portion of the earth's crust which is being prepared for its ultimate disintegration into soil. Great porosity, low temperature, and low pressure characterize this zone.

The *belt of cementation* is beneath the level of underground water. In this belt, as the name implies, deposition rather than solution plays the leading part. The consolidation of sands and clays into hard rock is brought about here, both by the deposition of minerals obtained by solution from the belt of weathering and also by the pressure of the overlying rocks. The rocks of this deeper zone are more or less porous and fractured, and the temperature is comparatively low.

As the surface of the land is lowered by erosion, the belt of weathering invades the belt of cementation, and the minerals which were deposited in the pores and cracks of the latter may again be dissolved out.

Desert Limestone. — In arid regions the underground water may, by capillarity, bring to the surface large quantities of lime which, upon evaporation, is deposited as *desert limestone.* About Valencia, Venezuela, for example, the underlying rock is almost entirely hidden by thick layers of this deposit, and extensive areas of New Mexico, Arizona, and other states are covered by this limy incrustation.

Mechanical Work of Ground Water. — The mechanical work of underground water is important in producing landslides (p. 73), but aside from this the effect is usually slight, since its movement is, for the most part, extremely slow.

An interesting result of the drying out of underground water was observed in England at the end of a prolonged drought in the summer of 1911. It was found that the foundations of hundreds of houses which rested on clay began to settle after the return of the rains. In ordinary summers the clay is quite moist at a depth of 2.5 to 3 feet below the surface, but during the summer mentioned it was often dry at depths of 5 to 6 feet. The dry clay became powdery, and when the autumn rains began the water found its way into the fissures and washed out the clay, causing sliding and lateral movements.

SPRINGS

The rain water which sinks into the soil and rocks through joints, fissures, and pores usually issues once more to the surface through seepage and springs (Fig. 37).

Origin of Springs. — (1) Springs commonly owe their existence to the presence of a stratum of pervious material overlying an impervious

FIG. 37. — Thousand Springs, Snake River, Idaho. (U. S. Geol. Surv.)

one. The water penetrating the pervious or fractured stratum (Fig. 38, *A* and *C*) is prevented from moving downward through the impervious layer whose slope it follows until it emerges at the contact of the two layers. (2) A second class of springs rise through cracks or fissures (Fig. 40). These are often of great volume and may have a temperature higher than the springs of the first type. (3) When the surface of a limestone region is lowered by streams (Fig. 39), an underground stream is often encountered and gives rise to the springs of great volume which are so frequent in such districts Silver Spring in Florida forms a navigable stream from its source. Springs may flow into valleys at, or above, the *thalweg*, which is a line following the lowest part of the valley.

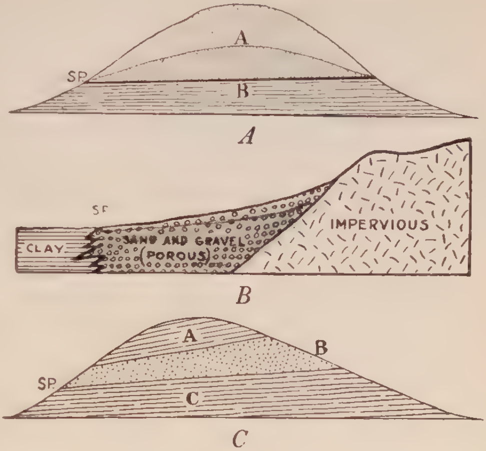


FIG. 38. — Diagrams showing the origin of springs. In *A* the porous stratum is indicated by dots, the saturated zone being shaded. *B* is an impervious stratum. A spring (*sp*) appears at the left, and during wet seasons, when the water table is high, a spring will flow also from the right of the hill.

Diagram *B* is a section showing high land on the right, impervious clay on the left, and gravel and sand between. Rainwater flows from the impervious high land to the porous gravel, into which it soaks, and comes up as a spring when it reaches the impervious clay.

C shows a porous stratum *B* overlain by an impervious stratum. In such a case the water is derived from the surface at *B* and appears as a spring (*sp*) at the left.

FIG. 39. — Large springs often issue from the base of limestone cliffs. Such springs are frequently contaminated, since their water enters through wide joints and sinks without being filtered by soil.

The oases of deserts often owe their existence to springs. The oases of Kerid in the northern Sahara desert contain about 6000 acres, which support nearly 1,000,000 date palms. They lie at the foot of an escarpment which forms the northern boundary of the desert. From the base of this escarpment or cliff, numerous springs gush forth and furnish a constant supply of water for irrigation. The water of the springs falls as rain in the highlands many miles distant. After flowing as streams for a short distance, the water disappears in the sand. It then follows underground courses until the escarpment is reached.

Fig. 40. — A fissure spring.

Constant and Intermittent Springs. — Whether springs are constant or intermittent depends upon a number of factors: if the rainfall is not uniformly distributed throughout the year, if the region is not forested, or if the porous rock is too limited to hold a sufficient supply of water, an intermittent spring may result. In such a hill as that shown in Fig. 38 *A* the glacial deposit (till) and sand allow the water to be absorbed in large amounts and to sink to the impervious stratum along which ground water flows to *Sp*. When the water stands at *A*, a spring may flow which will cease when the water is below that level. In unusually dry seasons all may disappear. It is seldom, perhaps never, that a siphon operates to form an intermittent spring, but in such a case as that shown in Fig. 41 it will be seen that the water will not flow until it has reached *BC*, after which it will discharge until the reservoir is empty. This is due to the fact that the weight of the water in the arm *CD* is greater than that of the arm *B*.

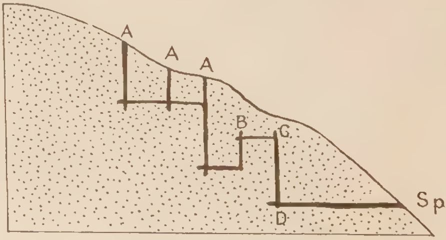


Fig. 41. — Diagram illustrating the possibility of the occurrence of a siphon spring in nature. If the vertical joints *B* and *C* do not reach the surface, the water filling the joints *A*, *A*, *A* will continue to flow as a spring (*Sp*) until the joints are emptied, because the weight of the water in the arm *CD* is greater than in *B*. When once emptied the water will not begin to flow until the joints are filled above *BC*. (Modified after De Martonne.)

Mineral Matter in Spring Water. — Since springs are derived from underground water which has been in close contact with various rocks, they usually contain a much greater quantity of dissolved minerals than do streams. Silver Spring in Florida is carrying to the sea in solution 340 pounds of mineral matter a minute, or 600 tons a day, and it is estimated that, in central Florida, a little more than 400 tons of rock a square mile are annually carried away in solution. This would be equivalent to a lowering of the surface of the central peninsular section of Florida by solution alone at a rate of one foot in five or six thousand years.

Falls Creek, Oklahoma (Fig. 71), receives water from springs which contain much lime carbonate. In the immediate vicinity of the springs, however, no deposits are formed, as there is a sufficient amount of carbon dioxide present in the water to hold the lime in solution, but by the time the stream has flowed a quarter of a mile large quantities of carbon dioxide have been given off, and travertine is deposited in the bed of the stream in the form of dams which vary in height from a few inches to 15 feet, and are being built up faster than the stream can cut them away.

FIG. 42. — Block diagram showing the formation of a travertine terrace and natural bridge. Water containing much lime carbonate emerges from springs in the limestone at the right. Travertine has been rapidly deposited, forming the terrace and natural bridge.

The great limestone deposits at Tivoli in Italy, from which was quarried much of the stone used in the construction of the Coliseum and St. Peter's at Rome and the interior of the Pennsylvania railroad station in the City of New York, were laid down by springs. The quantity and rapidity of the deposition of limestone under exceptionally favorable conditions is well shown in the great travertine natural bridge at Pine, Arizona, more than 125 feet high, which, together with a terrace of 25 acres, was formed by such a deposit (Fig. 42). Springs containing lime carbonate or gypsum in solution are called "hard," since, in washing, the fatty acids of the soap unite with the dissolved minerals to form the insoluble "curd."

By abstracting carbon dioxide from the water in which they grow algæ may cause lime to deposit. In this way beds of so-called "petrified moss," more than ten feet thick, have been formed. In the Yellowstone National Park the deposits about the geysers were built up both by the evaporation of the water and by algæ (p. 65). A reduction in temperature and pressure may also cause minerals in solution to be deposited, as may also the mingling of waters carrying in solution substances of different composition (p. 372).

Mineral Springs. — Mineral springs contain various salts or gases. Such springs are often called "medicinal" because of their supposed curative properties. The total value of mineral waters is large, amounting to $5,631,391, in 1913, in the United States alone.

Temperature of Springs. — The temperature of springs is usually much lower than that of the air in summer, being about 47° F. in Connecticut; and the water is often described as being "icy cold." The temperature of such springs in middle latitudes is fairly constant if they come from a depth greater than 50 or 60 feet, since at this depth the water is not affected by daily or seasonal changes and has, consequently, about the average temperature of the region.

Thermal Springs. — The temperature of many so-called hot springs varies from lukewarm to boiling. (1) The heat is sometimes due to the presence of deep fissures through which the surface water has percolated until it has reached great depths, where its temperature has been raised by the interior heat of the earth. After being thus heated, the water is forced by hydrostatic pressure to a point on the surface which is lower than the point of ingress. The depth from which come springs like those of Bath, England, which have a temperature of 120° F., may be approximately told from well borings, such as that of a well at Berlin, Germany, the water of which has a temperature of 110.5° F. at a depth of 3390 feet. Springs located along fissures in the earth's crust occur in Virginia, Arkansas, Colorado, Nevada, and South Dakota, and are often the seat of popular health resorts. (2) The water of some springs is heated by chemical action. (3) Water in volcanic regions may be heated at comparatively shallow depths by the presence of uncooled lava. Of this class there are more than 3000 in the Yellowstone National Park, some of which deposit limestone (travertine) and others silica (geyserite). Hot springs may bring about a considerable change in the character of the rocks in the regions in which they occur, by causing the disintegration of some and by adding new material to others. This is due to the fact that hot water is a more powerful solvent than cold.

Geysers. — Geysers are springs which intermittently erupt columns of hot water and steam (Fig. 43). They occur in regions of comparatively recent volcanic activity, where the lava is hot at a relatively shallow depth. They are well developed in but three localities in the world, and the total area occupied by them is probably less than ten square miles. The most notable geysers occur in Iceland, New Zealand, and the United States, although smaller ones are to be seen in Mexico, Tibet, the Azores, and the island of Formosa. Some of them throw water to a great height. The Monarch Geyser in New Zealand became active in 1903 and is said to have thrown mud and stones to a height of 1000 feet. Such a height, however, is unique. In the Yellowstone National Park an eruption throwing water 300 feet vertically is rare.

Fig. 43. — Lone Star Geyser, Yellowstone National Park.

The quantity of water flowing from geysers varies greatly: in the smaller ones it may be only a few gallons an hour, while in others, as in Old Faithful in the Yellowstone National Park, the discharge may be as great as 750,000 gallons an hour, a quantity sufficient to supply a city of 150,000 inhabitants. The water of geysers is rain water which has percolated through porous lava, and under normal conditions would be discharged as springs. Consequently, if the climate of the Yellowstone National Park should become arid, the geysers would disappear. This water, heated by its passage through the lavas, dissolves soda and potash, becoming alkaline and thus capable of dissolving silica from the silicates of the lavas. Accordingly, the waters erupted by geysers contain much mineral matter in solution, the chief of which is silica. This silica is deposited about the openings of the springs as siliceous sinter, or *geyserite*, forming a mound both by evaporation and also through the action of minute plants (algæ) which are capable of living in hot water and of secreting silica. It is stated that by evaporation alone a geyser can produce a maximum thickness of geyserite of one twentieth of an inch a year, while the increase from algæ deposition under favorable conditions may be as much as eight inches during the same period.

A geyser usually originates as a spring in a fissure, the opening of which is gradually built up by the deposition of siliceous sinter until a considerable mound or terrace is formed. As long as the tube through which the water reaches the surface is short or the circulation of the water unimpeded, a siliceous spring will flow. When, as a result of the building up of the mound or for other reasons, the tube becomes so long that the water cannot circulate with rapidity (Fig. 44), the water at some distance below the top of the tube will increase in temperature more rapidly than that at the surface. Eventually water at a depth of a number of feet will reach its boiling point with the resultant formation of bubbles of steam which, in turn, will cause the water to spill over the edge of the opening. This overflow promotes boiling by reducing the pressure upon the water deep in the tube. As a consequence a large quantity of water, which was not quite at the boiling point because of the weight of the overlying column of water, will instantly burst into steam and will eject the overlying water from the tube, sometimes to a great height. Usually the eruptions are not regular, but in Old Faithful an eruption can be predicted at intervals of about sixty minutes. When a quantity of soap or lye is thrown into a geyser, the viscosity of the water is increased and its circulation correspondingly lessened. In this way an eruption may be hastened. As the lavas cool, the geysers must necessarily disappear. However, the loss of heat is very slow, as is shown by the fact that, although careful records have been kept since the Yellowstone basin was discovered, the Yellowstone geysers have shown little sign of change since they were first studied. The eruptions of Old Faithful, for example, continue to be regular.

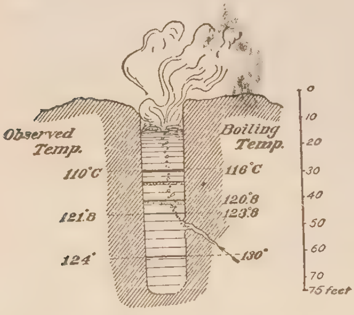


FIG. 44. — Cross section of a geyser, showing the boiling temperature at the right and the recorded temperature at the left. (After Campbell.)

Striking Effects of Ground Water

Sink Holes. — In limestone regions it is not unusual to find many funnel-shaped depressions in the surface of the ground into which water may flow. These are called "sink" or "swallow holes" and may be very conspicuous features of the landscape (Fig. 45). They are formed either (1) through direct solution by surface waters along joints, in which case they are usually more or less circular in outline; or (2) by the falling in of the roof of a cavern, when they are often irregular in outline. Those formed in the first way are much more common than the latter, but are usually smaller. An example of sink holes formed by the falling in of a cavern roof occurred in the city of Staunton, Virginia, in 1910, when four "cave-ins" occurred within three weeks, the largest of which was 60 by 90 feet. During the formation of this largest one three trees and portions of a dwelling house were engulfed. (3) In regions underlain by salt, local sinkings result from the solution and removal of the salt by underground water.


Fig. 45. — Small swallow or sink holes in the Juras, Switzerland.

After a sink hole is formed, more or less of the material immediately around the hole will be carried in by surface wash. Moreover, a large amount of water entering through the sink may cause a rapid solution of the limestone in its immediate vicinity, resulting in the formation of large basins locally called "prairies" or "coves." In the United States these are well developed in Kentucky and Florida.

If the bottoms of sink holes become choked, small lakes or pools come into existence. A striking example is shown in the history of Alachua Lake,[1] Florida. Previous to 1871 the waters of

---

[1] Florida Geol. Surv., Third Annual Report, 1910, pp. 62–67.

the principal stream of this region emptied into a sink or swallow hole in the Alachua prairie. By the choking of this outlet a lake was formed which, at its greatest extent, was eight miles long and in one place four miles wide and of sufficient depth to permit a number of freight steamers to ply upon it. After being choked for about twenty years the underground passage from the swallow hole was opened again, and the lake gradually disappeared.

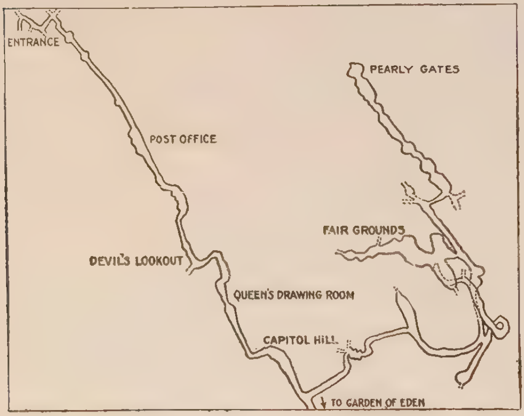


Fig. 46. — This map of Wind Cave, South Dakota, shows the relation of the underground passages to the jointing of the rock.

Caverns. — Caverns occur in limestone regions and are usually connected with sink holes by more or less distinct passages. They have been formed, with few exceptions, by the solvent power of the water which poured through the sink holes and joints, or seeped through the rocks from the surface, and, to some extent, through abrasion by the sediment carried by the subterranean streams. Since water circulates most rapidly along joints (Fig. 46) and bedding planes, it is in such positions that most rapid solution takes place, and it is here that caverns occur. In certain spots, owing to the presence of numerous open joints or to the solubility of the rock, large domes are formed. Solution is usually most effective in forested regions, since the humus affords a large and constant supply of carbon dioxide, without which water is but slightly solvent. Caves may, however, be formed by carbonated waters ascending from below; an example of which is the interesting and extensive Wind Cave in the Black Hills of South Dakota, which was formed by hot water coming up from a great depth and gradually enlarging the joints and fissures in its ascent.

In regions of thick limestone, caves at different levels, called "galleries," occur (Fig. 47); as, for example, in Mammoth Cave, Kentucky. These galleries are the result (1) of the presence of layers of relatively insoluble rock upon which the underground streams flow until they dissolve and erode out a wide passage. If this layer is worn through after a time, or a joint is enlarged, permitting the water to reach a lower soluble layer, it may descend until a second relatively insoluble layer is encountered. If this process is repeated, several galleries will result. The lowest level at which caves may be formed is that of the lowest surface stream into which the underground water is discharged. (2) Migration from one level to another may also result from the intermittent lowering of the valleys (Fig. 47) of the surface streams into which the underground waters of the caverns flow. The galleries of caves may divide and reunite, forming a network of channels at the different levels. It has been estimated that in Kentucky alone there are 100,000 miles of underground passages.

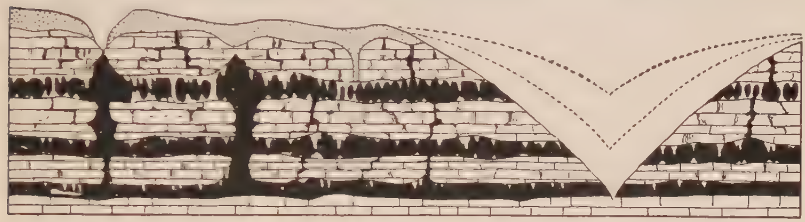


FIG. 47. — Diagram showing the formation of the galleries of limestone caves by the lowering of the valley (indicated by dotted lines) to which the underground water dissolving them flowed.

Natural Bridges may be formed by the partial caving in of the roofs of caverns, or by the enlarging of two sink holes opening to the same underground stream. Natural bridges are also formed in other ways (pp. 91, 112).

Cave Deposits. — After a cave has been abandoned by the stream which formed it, the water entering is confined chiefly to small seepage. At this stage much of the water is removed by evaporation so that solution gives place to deposition. The deposits in caves are usually in the form of *stalactites* and *stalagmites*. The former begin as a thin film of lime around the outside of a drop of water which evaporates on the roof of a cavern. Upon this additional lime is left by other drops until a stalactite, resembling an icicle, is suspended from the roof of the cavern. The accumulations of lime which form where the

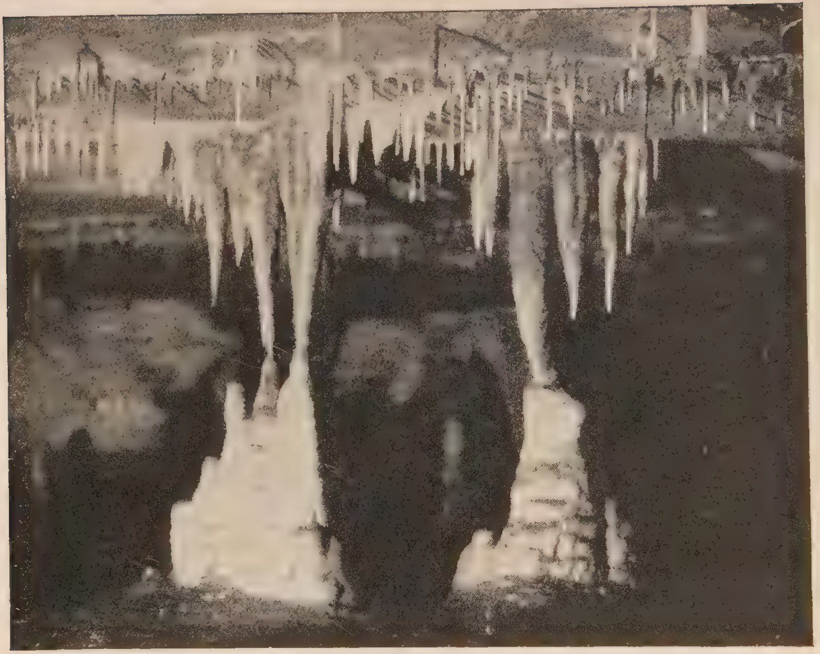


Fig. 48. — Stalactites and stalagmites in Marengo Cave, Indiana. (D. Appleton and Company.)

water evaporates on the floor of the cavern are known as stalagmites (Fig. 48). By the union of the stalactites and stalagmites *pillars* are formed.

Caverns are also formed in other ways (pp. 209, 298), but the great majority are formed from solution.

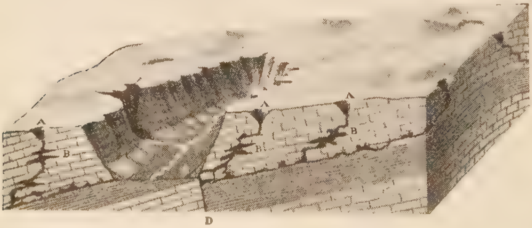


Fig. 49. — Block diagram of a karst (limestone) region, illustrating the effect of solution. Sink holes *A A A* drain the surface and discharge their water through underground channels to an open valley. Surface streams are lacking, and the main valley has steep sides. The spring at *C* may be very large. A fault is also shown at *C*. (Modified after De Martonne.)

Karst. — Karst is used as a descriptive term for any limestone region which has been etched and eroded by water into a rough surface (Fig. 49). The name is derived from Karst, on the east side of the Adriatic, where such a surface is developed upon a nearly pure limestone. It is a desolate region in which vegetation is scanty, except in sink holes (dolines), where the small amount of insoluble matter yielded by the rock accumulates and furnishes a soil for plants. The drainage is, for the most part, subterranean; and the surface is etched out into a network of narrow channels between which blade-like masses of rock rise. It is pitted with sink holes and, where important streams cross the karst land, they flow in deep gorges, rather than in ordinary valleys.

Landslides. — Landslides may result from a number of conditions, one of which is often associated with underground water. Soil and subsoil tend to move down a hillside when they become charged with water. If this movement is insensible it is called "creep"; if sensible, "slumping" or "sliding." Railroad tracks may be gradually moved down hill and trees be tilted by the slow movement of hillside creep.

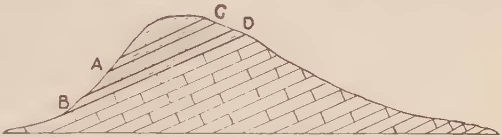


FIG. 50. — Conditions favoring landslides. The strata *AC* and *BD* are clay or shale which, when wet, are slippery, so that sliding is likely to occur.

The conditions favorable for a landslide are a steep slope upon which soil rests, or steeply dipping rock which has been undercut at the base, artificially or by streams, so that the upper layers are unsupported (Fig. 50). When, under either of these conditions, the soil or rock becomes saturated with water, its weight is increased, and, moreover, the water, acting as a lubricant, lessens the friction which previously prevented the soil or rock from sliding. Such was the cause of the Mt. Greylock, Massachusetts, landslide, in which a great mass of soil and glacial débris slid down the steep mountain side after a period of excessive rainfall; and of the landslide in Quebec, where the rock hillside slipped

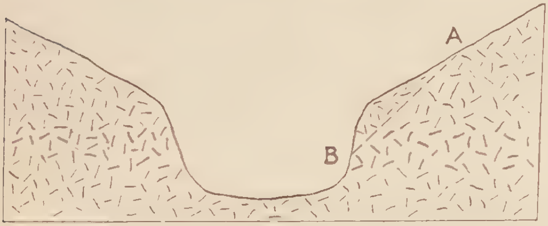


FIG. 51. — Diagram showing a valley which has been deepened by glacial erosion, leaving steep slopes unsupported on each side. Fractures may develop at *AB*, and a portion of the side may slide into the valley.

FIG. 52. — Landslide, Turtle Mountain, Alberta. (Photo. Hopkins.)

along a plane of steeply dipping slate which had been lubricated by underground water.

In mountainous regions, where the valleys are deep and the slopes steep, conditions are extremely favorable for landslides (Figs. 51, 52). One of the most destructive of such slides occurred on the Rossberg in Switzerland in 1806. Here the rocks high up on the mountain slid suddenly into the valley, burying the village of Goldau and causing the death of several hundred people. Masses of rock, some of which were as large as houses, were spread over the valley for two or three miles. Evidences of many prehistoric landslides are to be seen in Switzerland, as well as in other mountainous regions. At Siders a landslide is spread out for several miles across the Rhone valley, and some of the hills formed from the material of the slide are almost 200 feet high. So marked is this landslide topography that it forms the boundary between the French and German-speaking people in the Rhone valley.

FIG. 53. — A lake in eastern France formed by a landslide. The character of the material of the dam is shown in the foreground.

Conditions favorable for landslides were created artificially in the excavation of the Culebra Cut in the Panama Canal, where the rock will continue to slide periodically until a gentle slope is formed. During a single year (1911) nearly 36 per cent. of the total material excavated had been brought in by landslides.

Landslides may dam streams, forming lakes (Fig. 53) or rapids. Lake Oechenen, in the Kandersteg valley of Switzerland, and the Cascades of the Columbia River were formed by landslides broken from the high mountains a few centuries ago. The rounded hills and basins sometimes produced by landslides are very similar in appearance to those formed by glaciers (Fig. 54). Moreover, the heterogeneous clays and angular bowlders of which they are composed resemble glacial débris. The rocks of landslides, however, instead of being scratched, as is true of glacial bowlders, often show *impact marks*, formed by the striking of one rock against another in their violent descent down the mountain side.

Fig. 54. — Landslide topography which has much the appearance of a moraine. Kandersteg valley, Switzerland.

CONCRETIONS

Although concretions are usually of little geologic importance, they occur so frequently in the rocks and sediments of the earth and excite so much interest that they deserve some attention (Fig. 55).

Concretions are masses varying greatly in shape and in size from less than a pinhead to more than 10 feet in diameter, and are formed by the gradual segregation of mineral matter. The shape, as has been said, varies greatly. Some concretions are spherical, some are flat, and others curved. The odd shapes which resemble animals (Fig. 55) are usually produced by the growth of two or more concretions until they join. The center of attraction may be a fossil or a bit of mineral, but in the majority of specimens no nucleus can be detected. In some formations (for example, the Arikaree, Miocene, in Nebraska) they may, by their abundance, so strengthen the loose sands and clays containing them as to form a resistant bed which stands as cliffs wherever cut by streams.

Fig. 55. — Clay-stone concretions of various shapes. They are composed largely of lime carbonate and occur in clay.

Concretions usually occur in definite beds in a formation, and it is sometimes possible to trace such beds for several miles. They occur in rocks of every age, from the most ancient to those now forming on the bottoms of lakes and seas.

Composition of Concretions. — Concretions are seldom of the same composition as the containing rock; those occurring in limestone are apt to be of silica; in clays and shales, of lime or iron carbonate; in sand and sandstones, of iron oxide or lime carbonate. Lime concretions, or clay stones, are probably more abundant than any others.

When concretions of limestone and iron carbonate (clay ironstones) are much cracked in the interior and the cracks filled with calcite or quartz, they are called *septaria* (Fig. 56). In sandstone iron concretions of two kinds may occur: "spherical," in which a spherical shell surrounds a core of sand, and "pipestem," which, as the name implies, are cylindrical. The former are probably formed as the result of the chemical change of some iron mineral in the rock, such as pyrite, which renders the latter soluble. After being thus changed, "it spreads outward as a drop of ink does on blotting paper. Evaporation takes place around the outer margin of the solution, iron oxide is precipitated, and the first ring or shell is formed." (J. Geikie.) Pipestem concretions are formed where soluble iron compounds are oxidized about the tubes produced by the roots of plants.

Fig. 56. — A polished section of a septarium. The white veins are calcite, the darker portions chiefly iron carbonate.

It is probable that certain masses of gravel in southern California which now stand up as hills have been cemented together by a kind of concretionary action.[1]

The flint nodules that are so abundant in the chalk of southeastern England sometimes had their beginnings in sponges which secreted a siliceous skeleton, and in other fossils. Upon this small quantity of silica as a center, other silica taken from the sea water was added to form the nodular flints. Since by a microscopic examination the structure of the chalk in which the nodules lie can be traced, it is evident that the flint nodules were formed in the chalk mud of the ocean floor, rather than on top of these sediments.

Time of Formation. — Lime concretions or clay stones are formed by the gradual accumulation of lime carbonate, and during their growth they inclose portions of the sediments in which they lie. They are often formed before the rock containing them is hardened (indurated), as is shown by the facts that (1) they are often cut by joints and (2) when they contain fossils, these remains are seldom flattened by the pressure of the overlying rocks as are those in the surrounding shale. Although many of the concretions which occur in sedimentary rocks were formed while they were in an unconsolidated state and before they were deeply buried, there is no doubt that some were formed after the sediments had been consolidated into rock.

Oölitic Limestone (Greek, *oön*, egg, and *lithos*, a stone), so-called because of its resemblance to fish roe, may be almost completely com-

---

[1] Arnold, R., — Jour. Geol., 1907, Vol. 15, pp. 560–570.

posed of minute concretions (Fig. 57). Limestone of this origin (p. 249) is often widespread and many feet in thickness. It is, however, held by some investigators that the most of the oölitic limestone is the product of microscopically small algæ (plants) capable of secreting lime.

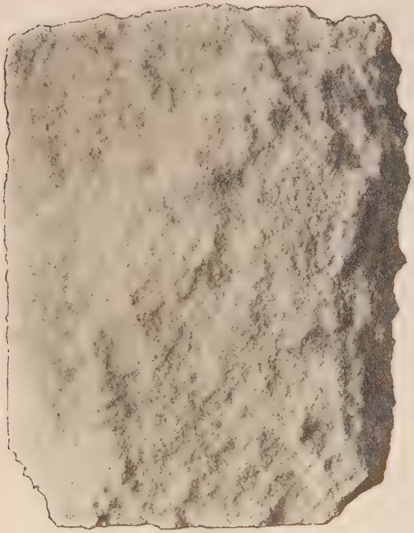


Fig. 57. — A hand specimen of oölitic limestone. (U. S. National Museum.)

Geodes. — Geodes differ from concretions in that they are formed in cavities of the rock and from *without inward* (Fig. 58). When lava contains steam cavities, silica may be deposited on the walls of the cavities and, by slow addition, may in time fill them. In this way *agates* are formed, the colored layers of which are due to coloring matter carried in and deposited with the silica. Many geodes owe their origin to concretions which were dissolved from the inclosing rock: in the cavities thus formed quartz, calcite, and other minerals were deposited, partly, but not entirely, filling them.

Fig. 58. — A geode broken in two. Cheyenne River, South Dakota.

REFERENCES FOR UNDERGROUND WATER

Springs

Bowman, I., — *Forest Physiography*, pp. 41–61.

De Martonne, E., — *Géographie Physique*, pp. 342–347.

Fuller, M. L., — *Occurrence of Underground Waters:* Water-Supply Paper, U. S. Geol. Surv. No. 114, 1905, pp. 18–40.

Gregory, H. E., — *Underground Water Resources of Connecticut:* Water-Supply Paper, U. S. Geol. Surv. No. 232, 1909, pp. 60–76.

Slichter, C. S., — *The Motions of Underground Water:* Water-Supply Paper, U. S. Geol. Surv. No. 67, 1902.

Weed, W. H., — *Formation of Travertine and Siliceous Sinter by Vegetation of Hot Springs:* Ninth Ann. Rept., U. S. Geol. Surv., 1889, pp. 613–676.

Woodward, H. B., — *The Geology of Water Supply*, pp. 79–95.

Artesian Wells

Chamberlin, T. C., — *Artesian Wells:* Geology of Wisconsin, Vol. 1, 1883, pp. 689–701.

Chamberlin, T. C., — *The Requisite and Qualifying Conditions of Artesian Wells:* Fifth Ann. Rept., U. S. Geol. Surv., 1885, pp. 125–173.

Darton, N. H., — *Geology and Underground Water Resources of the Central Great Plains:* Professional Paper No. 32, U. S. Geol. Surv., 1905, pp. 190–372.

Karst

De Martonne, E., — *Géographie Physique*, pp. 462–472.

Geikie, J., — *Earth Sculpture*, pp. 266–277.

Katzer, F., — *Karst und Karsthydrographie*, 1909.

Knebel, W. V., — *Höhlenkunde mit Berücksichtigung der Karstphänomene*, 1906.

Caves

Blatchley, W. S., — *Indiana Caves and their Fauna:* Twenty-first Ann. Rept., Ind. Geol. Surv., 1897, pp. 121–212.

Hovey, H. C., — *Celebrated American Caverns.*

Martel, E. A., — *Les Abîmes.*

Matson, G. C., — *Water Resources of the Blue Grass Region:* Water-Supply Paper, U. S. Geol. Surv. No. 233, 1909.

Shaler, N. S., — *Aspects of the Earth*, pp. 98–142.

Concretions and Geodes

Arnold, R., — *Dome Structure in Conglomerate:* Jour. Geol., Vol. 15, 1907, pp. 560–570.

Geikie, J., — *Structural and Field Geology*, pp. 120–124.

Grabau, A. W., — *Principles of Stratigraphy*, pp. 718–721.

Gratacap, L. P., — *Opinions upon Clay Stones and Concretion:* Am. Naturalist, Vol. 18, 1884, pp. 882–892.

Merrill, G. P., — *Rocks, Rock-Weathering, and Soils*, pp. 35–37.

Nichols, H. W., — *New Forms of Concretions:* Field Columbian Museum, Geol. Series, Vol. 3, No. 3, 1906, pp. 25–54.
Sheldon, J. M. C., — *Concretions from the Clay Stones of the Connecticut Valley.*

General

Hobbs, W. H., — *Earth Features and their Meaning*, pp. 180–194.
Ries and Watson, — *Engineering Geology*, pp. 295–357.

Topographic Map Sheets, U. S. Geological Survey, Illustrating the Work of Ground Water

Arredondo, Florida.
Bristol, Virginia–Tennessee.
Weingarten, Missouri–Illinois.
Princeton, Kentucky.
Kingston, Tennessee.
Greenville, Tennessee–North Carolina.
Williston, Florida.
Standingstone, Tennessee.
Lockport, Kentucky.
Waterloo, Illinois.

CHAPTER IV

THE WORK OF STREAMS

It is difficult to over-emphasize the importance of streams, since they carry off the excess of rainfall above evaporation, with the exception of the ground water which enters into chemical composition with rocks or is discharged in underground courses directly to the seas (p. 56). The quantity of water carried in streams is therefore enormous. It has been estimated that the rivers of the world annually discharge 6500 cubic miles of water; a volume which, if spread over Massachusetts, would cover it three quarters of a mile deep. The water of flooded streams is derived largely from rainfall, while the chief source is spring water, when they are low.

Factors in Stream Erosion

Material Carried by Streams. — In walking up a small valley one can readily discover the sources of the gravel and sand in the stream bed, and of the mud which renders the water turbid. The small particles which have been broken from the rocks of the banks by the various agents of the weather, and the larger fragments which have been loosened by frost are continually being carried down into the bottom of the valley by gravity (hillside creep, p. 73) and washed down by rains; deposits of sand and clay through which the valley is cut in places furnish an easy supply during floods; the solid rock of the valley sides, when undercut by the stream, falls into the water; and some sediment is obtained from the bed over which the stream flows.

How the Sediment is Moved. — Streams accomplish their work of removing this load of sediment (1) by pushing along the larger of angular rocks, (2) by rolling the rounded and smaller pebbles, and (3) by carrying in suspension the finer sand and clay, as well as such thin, flat particles as mica flakes. This ability of running water to carry fine particles in suspension is due to the fact that the smaller the volume of an object, the larger in proportion is its surface. This being the case, a slight upward current, formed by the deflection of the water from the irregularities of the stream bed or side, will lift small particles and carry them onward until they again fall to the bottom, or are caught up by another current (Fig. 59). The eddies and cross currents of a river are especially effective in this work during high water. In this way, sand and clay, after many short journeys, are ultimately carried to the ocean. The quantity of sediment carried by a stream depends upon its volume and velocity and on the amount and nature of the accessible material.

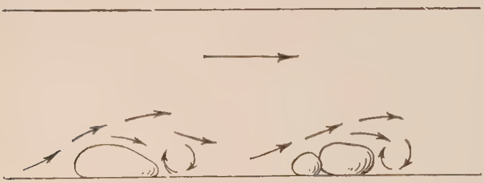


Fig. 59. — Diagram showing how upward currents are produced by irregularities on the bed of a stream.

Factors Determining the Velocity of Streams. — The velocity of a stream depends upon (1) the slope of its valley, (2) its volume of water, (3) the amount of its load, and (4) the shape of its channel. It is greatest in the middle of the stream, and some distance below the surface. If the volume of a stream is increased eight times, its velocity is doubled, since the velocity varies as the cube root of the volume; if the amount of the sediment is decreased, the velocity is increased; and, other things being equal, a stream following a straight channel flows faster than one in a winding course, because it loses less energy in friction with its sides. A stream which is ordinarily clear is often muddy when swollen, both because of the greater run-off which enters it, and because of the large amount of sediment which it is enabled to tear from its bed and banks on account of its greater velocity.

If the velocity of a stream is increased several times, its power becomes almost incredible. It has been shown that a current moving six inches a second will carry fine sand; one moving 12 inches a second will carry gravel; four feet a second, stones of about two pounds weight; eight feet a second, stones of 128 pounds; 30 feet a second, blocks of 320 tons; if a stream can ordinarily move a pebble of one ounce, it can move a stone of four pounds when doubled by a flood. This fact is expressed in the law that *the transporting power of a stream varies as the sixth power of its velocity.* Keeping the above law in mind and remembering that a heavy object loses about one third of its weight in water, it is easy to understand the cause of the destructiveness of such floods as that which overwhelmed Johnstown, Pennsylvania, in 1889, and swept away large rocks, twenty-ton locomotives, and massive iron bridges as easily as, under ordinary circumstances, the river could move sand. A fall of one foot in a mile is quite sufficient to carry a river steadily onward; one foot in a thousand feet will make a fairly rapid river; one in two hundred, a torrent.

Water Wear. — The pebbles and sand carried by the streams are worn away by their impact against the bed rock and by striking against each other. The result of such wear is the production of rounded stones. In mountain streams the angular fragments from the talus are rounded before they have been carried a mile.

Solution. — In addition to the sediment carried by the force of the current, the waters of every river contain a large amount of mineral matter in solution. This is largely obtained from springs, but also from the run-off and by the solution of the stream bed. The amount in any stream varies with the season, being greater in proportion to the volume of water in dry than in wet seasons, since in the former the water is largely underground water. The small river Thames, England, carries to the sea about 348,230 tons of dissolved minerals a year, and the Mississippi River carries 113,000,000 tons. "The Rhine carries enough carbonate of lime to the sea each year for the annual formation of 3,320,000,000 oyster shells of the usual size." (A. Geikie.) It is estimated that in every 5000 years rivers carry their own weight of minerals in solution to the sea. The weight of the dissolved matter carried to tidewater by the streams of the United States (270,000,000 tons) is more than half that of the sediment (513,000,000 tons).[1] "The tons per square mile per year removed from different basins show interesting comparisons. In respect to dissolved matter the southern Pacific basin heads the list with 177 tons, the northern Atlantic basin being next with 130 tons. The rate for the Hudson Bay basin, 28 tons, is lowest; that for the Colorado and western Gulf of Mexico basins is somewhat higher. The denudation estimates for the southern Atlantic basin correspond very closely to those for the entire United States." (Dole and Stabler.)

Vertical Erosion (Corrasion).[2] — By erosion (Latin, *erodere*, to gnaw away) streams are able to cut down their valleys. This may be

---

[1] Water-Supply Paper, U. S. Geol. Surv. No. 234.

[2] The terms *corrasion*, *abrasion*, *corrosion*, *erosion*, and *denudation* have sometimes been used rather loosely in geological and geographical literature. In this work *corrasion* (Latin, *corra-*

accomplished by (1) the mere impact of the water, especially if the rock is easily disintegrated (Fig. 60). The effect of clear water upon striking loose sediment with great force is well shown in hydraulic mining. This principle was also employed in the leveling of a portion of Seattle, where a high hill was cut down by means of a powerful stream of water. (2) In thinly bedded rocks, such as shales (p. 250), the stream bed may be deepened by "lifting"; that is, the shale, broken by joints, is separated by the water along the bedding planes (p. 234); and the fragments are thus floated off. The effect of this process alone in regions underlain by shales may be of the greatest importance. "Lifting" is especially effective when the stream beds have been exposed to the weather at low water. At such times, temperature changes or frost may loosen much material in the bed, which is picked up and removed during high water. Water without sediment has little effect in eroding thick

FIG. 60. — A bank undercut by clear water. (U. S. Geol. Surv.)

---

dere, to rub) and *abrasion* are used as synonyms, meaning the detachment of rock particles as a result of wear; *corrosion* (Latin, *corrodere*, to gnaw) is used for the work done by solution; *erosion* is used to include both corrasion and corrosion, as when we say a river erodes its valley, or a sea erodes its shores. The term *denudation* is reserved for the lowering of a land surface by any agency.

bedded rocks, as is apparent on the brink of Niagara Falls where the thousands of tons of water which pour over them hourly are unable to remove the soft algæ which cover the rocks, as the water is filtered by Lake Erie. (3) When swift streams are supplied with tools (Fig. 61) in the form of sand and pebbles, their erosive power becomes greatly increased.

Fig. 61. — Bowlders in a stream bed. Here the bowlders form a pavement which hinders the erosion of the valley.

Weathering and Vertical Erosion. — Even very young valleys are usually wider at the top than at the bottom. This is due to the fact that while the valley is being deepened by erosion it is also being widened in several ways. The rock is loosened by the various agents of the weather and carried to the stream by rainwash and wind. Normally, valleys are most rapidly widened in temperate regions, since there the soil freezes and thaws frequently so that "creep" (p. 73) plays an important rôle. Valleys cut in sand or clay are often widened to a considerable degree as a result of the pressure of the overlying sediment, which forces the unconsolidated sand or clay at the base to "flow out," causing a slumping of the upper portion. Animals walking on the slopes, falling trees, the cutting of the stream against its sides are among the agents which help to loosen the material of the valley sides and thus tend to widen the valley. If erosion is very rapid as compared with the work of the agents of the weather, steep-sided gorges barely wide enough to accommodate the stream will result: such are the gorge of the Aar at Meirengen, Switzerland, the picturesque gorges of Watkins Glen and Ausable Chasm, New York, and the canyon of the Virgin River in Arizona. Usually, however, young valleys are V-shaped, the wearing back of the sides more than keeping pace with the deepening of the valley.

Base Level of Erosion.[1] — If a stream is swift, it continues to deepen its valley as it flows from the higher lands to the sea, until at or near the mouth, the bed will be at, or even slightly below, sea level. (The bed of the Mississippi River is locally as much as 100 feet below sea level.) The entire length of the valley, however, will not be deepened to the level of the sea, since as its slope (gradient) is diminished, the ability of the stream to erode its bed also decreases, and before sea level is reached the stream will have ceased to deepen its valley in its upper course. When this condition is attained, the stream is said to be at *base level;* that is, it has reached the lowest level to which a stream can wear a land surface. As the stream approaches base level, its current becomes less and less rapid, so that the deepening of the last few feet of the valley may take longer than all the rest.

If the land is raised and the gradients of the streams are increased, they will again cut until a new base level is reached. If on the other hand the land is lowered, base level will be reached more quickly.

During their histories streams usually reach a number of temporary base levels. If, for example, a stream flows into a lake, it cannot cut lower than that level; and if the lake remains in existence for a long time, the stream will excavate a broad valley where it enters the lake. Again, if a stream flows over a stratum of hard rock in its lower course while its upper course is in less resistant rock, the depth to which it cuts in the hard rock will be the temporary base level, and a broad valley will be developed above the resistant rock, while the latter will constitute the steep-sided *narrows* so characteristic of the scenery of eastern Pennsylvania.

Effect of Load. — Whether a stream carrying sediment will erode or deposit depends upon its velocity and upon the amount of material. If its velocity is great, the sand and gravel will be used as tools with which to cut down the stream bed, or widen it. If, however, the velocity is sufficiently decreased, as frequently occurs when a side stream with a steep gradient flows into a master stream with a

---

[1] The term *base level* has been used in several senses, the difficulty arising because of the fact that as commonly used the surface described is a *slope* and not a level plain. It has been suggested that "base level" be limited to the level base with respect to which normal subaërial erosion proceeds; to employ the term *grade* for the balanced condition of a mature or old river; and to name the geographical surface that is developed near or very near the close of a cycle a "peneplain" or "plain of gradation." (Davis, Wm. M., — *Geographical Essays*, p. 387.)

As used in this volume a *base level* is the lowest possible slope to which a region can be cut by running water. Thus a stream in a canyon may cut its channel to base level ages before it develops a plain at that level. A peneplain is any extensive tract of land reduced to essential planeness (base level) by the erosion of running water.

gentle grade, it may drop its load. Decrease of volume due to evaporation and to the absorption of the water by the soil, such as takes place when a river flows through a dry region, may reduce the stream's velocity to such an extent that it is unable to carry its load of sediment. The Platte River of Nebraska is a typical example of such a river. Its headwaters have a small amount of sediment in proportion to the volume of water, and it is therefore able to cut a deep canyon in its upper course; but in passing over the dry and thirsty plains it loses so much water that it is not only unable to degrade its bed, but even deposits much of its load during the dry season. A stream which flows over such sandy plains has shallow, crooked channels and is constantly shifting its course by cutting away the banks in some places and forming bars in others. When the load is so great that it is deposited in the channel, the latter may become too small for the water of the stream, in which case the water will break out and follow a new course. If this is repeated many times a network of small, shallow streams, called a *braided stream* (Fig. 62), may result. The Colorado and Platte rivers have about the same gradient, but the former receives less sediment in proportion to its volume and consequently is able to cut a great canyon, while the lower Platte flows in a broad and shallow valley.

FIG. 62. — Braided stream, Kandersteg valley, Switzerland.

When a stream has developed a slope which gives it just sufficient velocity to carry its load, leaving no energy for deepening its bed, it is said to be *graded.* If a stream has less sediment than it can carry, it will remove material from its bed. If it is unable to transport all the sediment brought to it, part of this will be left as a deposit, the channel will be raised, and the gradient will be increased until the stream becomes swift enough to carry away its load. When a stream is at a temporary base level (p. 86) above a fall or rapid, there are often smooth reaches where the stream is at grade. If the land through which a river flows has not been elevated or depressed for a long period of time, few falls will exist, and it will be at grade for long stretches. If, however, a long-continued uplift or several uplifts have occurred, even large rivers may be unable to erode their beds to grade. Even when the last uplift was so remote that the large rivers have been able to develop well-graded courses, the tributaries may, and usually do, have a steep slope.

Factors Affecting the Rate of Erosion. — The rate of erosion of a stream depends upon a large number of factors. (1) Loosely compacted rocks, or rocks with a soluble cement, are easily eroded. If, for example, the grains of a sandstone are held together with lime, the solution of the cement will cause the grains to fall apart and thus render the work of the stream easier. (2) Rapid erosion is further favored if the rock has numerous joints and is thin-bedded (p. 24). Usually sedimentary rocks are more readily eroded than massive, crystalline rocks (p. 330) such as granite. (3) The greater the velocity of a stream, the greater, other conditions remaining the same, will be the erosion. Since the velocity of a stream depends upon the volume of water as well as upon the slope of its bed, the cutting power will be greater during floods (p. 82). (4) Under any of the above conditions erosion will be favored if the stream has sufficient sand and gravel with which to cut its bed but not so much that a large part of its energy is expended in carrying it. When the amount of sediment is increased without an increase in the volume of water (p. 86), or when the quantity of sediment remains constant but the volume of water decreases, erosion may cease and deposition take place. Rapid erosion by abrasion requires some sediment, but not too much, a steep slope, and a considerable volume of water.

Scour and Fill. — A stream at flood may be deepening (degrading) its channel where its velocity is great, at the same time that it is building up (aggrading) its flood plain where the velocity is slight. After the flood has subsided the channel thus deepened may be entirely filled with sediment. This process is called *scour and fill.* The Missouri River sometimes scours out its channel to depths of from 70 to 90 feet and later fills it again. It is evident that the deepening of the beds of such rivers is largely confined to high water. A failure to understand scour and fill has led some observers to assign a great age to stone implements found deeply buried in river gravels (p. 680).

Lateral Erosion. — When a young river is deepening its valley it flows in a narrow channel between steep banks, but since its course is seldom straight it tends in places to cut more on one bank than on the other, with the result that as it cuts downward it also cuts sidewise, thus widening its valley. By the time grade is reached the valley walls will have flared open, but will be steeper on the outside of each curve. *Unsymmetrical valleys* are formed (1) in this way and also (2) by the greater hardness of the rock on one side of the stream than on the other (Fig. 63) (where the strike of the rock parallels the course of the stream).

FIG. 63. — Unsymmetrical valley formed as a result of the dip of the rock.

When two neighboring streams have ceased to degrade their beds, they will cut laterally and may in time wear away the divide which separates them, thus causing one to flow into the other.

FEATURES DUE TO STREAM EROSION

Falls and Rapids. — Falls and rapids result from a number of causes. (1) Regions in which a harder layer of rock overlies a softer one furnish most favorable conditions for the formation of falls (Fig. 64). When a stream, in deepening its valley, encounters a harder bed of rock lying in the position shown in the diagram (Fig. 65), the less resistant beds are worn more rapidly than the harder ones, and a rapid will result first, which upon further erosion will become a fall. Falls become lower and lower in the course of time, until the resistant beds form mere ledges in the stream bed and the falls cease to exist (Fig. 65). Niagara Falls (Fig. 66) have gradually cut back until now they are seven miles from their original position. The recession of these falls and their verticality are due to the fact that the strata which compose the higher land consist of massive limestone, about 80 feet thick at the falls, which are underlain by soft and easily weathered and eroded shale. When the water plunges over the limestone, it wears away the soft rock beneath more rapidly than the hard capping stratum, leaving the latter projecting. Fragments are continually falling from this overhanging ledge and are used by the water as tools to excavate the shale further. This erosion is also aided materially by blocks of ice in winter. The height of the falls is about 165 feet, and the gorge which has been excavated is from 200 to 400 yards wide and

Fig. 64. — Falls of the Genesee River, Rochester, New York. (Photo. C. R. Dryer.)

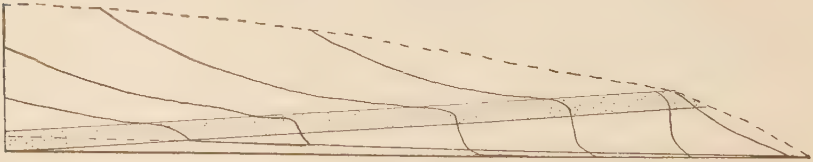


Fig. 65. — Diagram illustrating the recession of a waterfall formed by a resistant bed that dips up the stream. (Modified after Salisbury.)

about 300 feet deep in places. The rate of cutting of the Canadian Falls has been about 4.5 feet a year since 1842, while that of the American Falls, because of the smaller volume of water, is as small as 0.2 foot a year.

A natural bridge may be formed when the water above a fall percolates through a joint or crack athwart the stream and thence along a bedding plane or approximately horizontal crack, emerging under the fall as a spring. If the cracks are enlarged by solution and erosion, a tunnel large enough to accommodate the entire volume of the stream may be formed, and a natural bridge result (Fig. 67).

Fig. 66. — An ideal section of Niagara Falls, showing how the soft shales are being worn away, leaving the limestone above unsupported. (Gilbert.)

(2) When the fall of a river in working up stream passes the mouths of tributaries falls develop in them also. The beautiful Minnehaha Falls of Minnesota are an example of falls formed in this way.

(3) In mountainous regions, where the main streams have deepened their valleys rapidly their tributaries are often unable, because of their smaller volume, to keep pace with them and therefore flow into them over falls or rapids. To this cause the "roaring brooks" of New England are for the most part due.

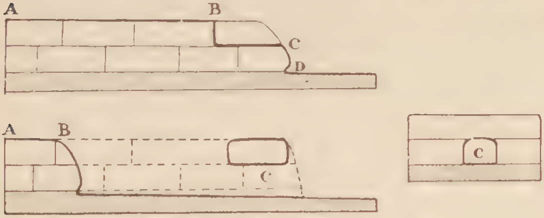


Fig. 67. — Diagrams illustrating the formation of a natural bridge by the widening of a joint or other crack *B* athwart the stream, through the solution of the limestone by water which reappeared as a spring under the fall at *C*. In the process of time a tunnel sufficient to carry a large part of the volume of the stream was excavated, and finally the entire volume of the stream. When this was accomplished a natural bridge (shown in the cross section) spanned the valley.

(4) The Atlantic coast, from New York southward, is bordered by a low-lying plain (Coastal Plain, p. 224) composed of soft, unconsolidated sands and clays. To the westward, this belt joins a belt of older and harder rocks (Piedmont Plateau) along a line roughly parallel with the coast.

When streams on their way to the sea pass from the hard to the soft rocks they flow over rapids or falls, because the less resistant rocks are cut down more easily than the hard. The boundary between the Coastal and Piedmont plains is for this reason called the "Fall Line," and it is here that many cities are located, both because the falls furnish water power and because they determine the head of navigation.

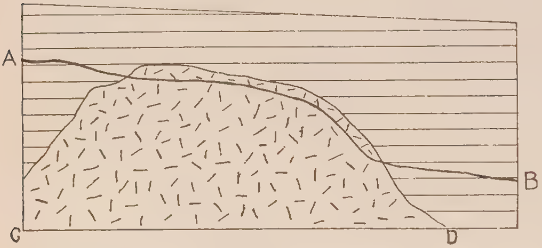


FIG. 68. — A fall formed when resistant rock is encountered by a stream. The rock *CD* is hard gneiss, while that represented by lines is softer schist. The line *AB* is the profile of the stream.

(5) When a stream in cutting its bed encounters a hard rock mass, the erosion of the valley is retarded at that point, but may continue farther down the valley. A fall or rapids (Fig. 68) will naturally be formed at such a place, and the hard rock mass will constitute a temporary base level which will prevent the stream from deepening its bed above the fall. As a result of the lateral erosion of the stream and of the action of the weather, the valley above the fall may be greatly widened, forming arable land. An example somewhat similar to the above is that of the falls of the Yellowstone, which are the result of the presence of lava, made more resistant by heat (Fig. 69). If rocks are less jointed or fractured in one portion of a valley than in another, they are less affected by erosion and may produce a fall or rapids.

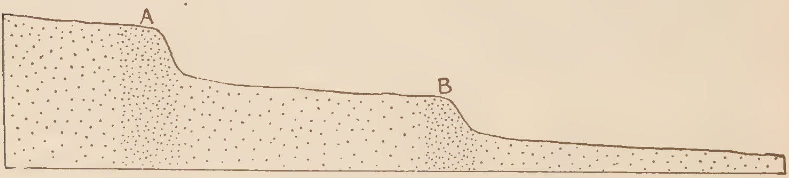


FIG. 69. — The falls of the Yellowstone River. The rock is lava, and the falls at *A* and *B* are due to the superior hardness of the lava at these points.

(6) Falls also result where rocks have strongly vertical joints, as vertical joints in homogeneous rocks have the effect of vertically inclined beds.

(7) The numerous falls of Switzerland were formed much as in (3), but are largely due to the erosion of the main valleys by glaciers so that the tributary streams enter their mains over falls. These side valleys are called "hanging valleys."

Exceptions — Falls not the Result of Erosion. — (1) A lava stream (Fig. 70) may dam a valley and thus produce a fall. Many examples of this sort might be cited. (2) Limestone (travertine) may be deposited in streams in such quantities as to dam them, forming falls (Fig. 71) and even ponding back the water to produce lakes. Topolic Falls in Dalmatia, east of the Adriatic, afford an illustration of the construction of a travertine dam. These falls are 70 feet high and are advancing downstream. (3) When tributary streams with steep gradients carry a large quantity of coarse débris, they may deposit their loads in the main stream in such amounts as to form temporary rapids. Landslides also accomplish the same result. The Cascades of the Columbia River were formed thus. (4) When a stream is forced out of its valley by landslides (p. 73), glacial deposits (p. 155), or in any other way, falls may result.

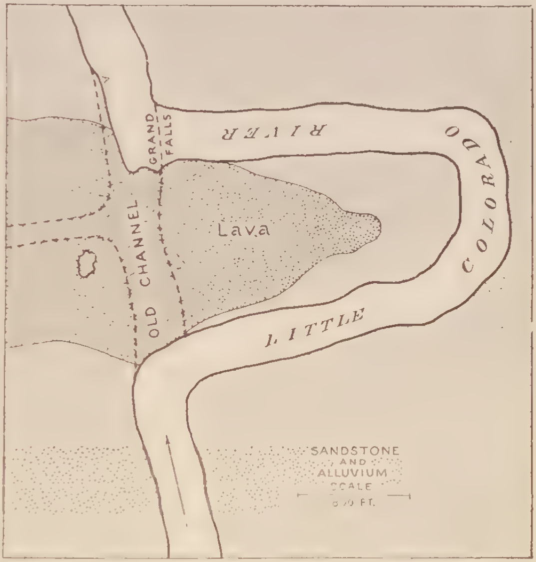


Fig. 70. — Falls formed as a result of the damming of a river channel by lava. (Modified after H. E. Gregory.)

Potholes. — When for any reason a strong, permanent eddy is produced in a stream, as at falls or rapids, pebbles and stones are given a rotary motion as they are carried through the eddy and wear down the stream bed in this place, tending to produce circular holes. These "potholes" (Fig. 72), "washtubs," "giant's caldrons," or "kettles," as they are called, occur in hard granites as well as in shales and limestone, and may be seen in the bed of almost any rapid

FIG. 71. — Travertine Falls near Davis, Oklahoma. The travertine which has been deposited to form these dams comes from springs containing large quantities of calcium carbonate in solution. The lime carbonate is deposited as travertine when the carbon dioxide escapes. Forty-four dams occur in this creek within a mile. (Oklahoma Geol. Surv.)

stream. They vary in diameter from a few inches to ten feet or more and in depth to forty or more feet. The size of a pothole depends upon the velocity and volume of the current and the length of time during which the eddy remains at the same point. By the deepening and coalescing of potholes the channels of streams may be materially deepened, streams sometimes accomplishing their greatest work of erosion in this way. In the Alps there is scarcely a gorge throughout the length of which one cannot see the polished surfaces and regular curves which are the traces of more or less complete potholes.

FIG. 72. — Potholes in gneiss, Shelburne Falls, Massachusetts.

Canyons. — Canyons are deep valleys with steep sides. They are formed where the down-cutting of a stream (corrasion) greatly exceeds the weathering back of the slopes. The conditions favoring the formation of such valleys are (1) a rock capable of maintaining a steep face, such as resistant rock on which the trickling water cannot act quickly, or a firm, permeable rock into which a large part of the water soaks, leaving little for erosion; and (2) a rapidly cutting stream. (3) An arid climate is more favorable than a moist one, since the work of the weather will be at a minimum in the former. Canyons are nevertheless formed in regions of heavy rainfall (Fig. 64). When a stream approaches base level and ceases to corrade its bed rapidly, the walls of its canyon will be weathered back until in time they form a broad, open valley.

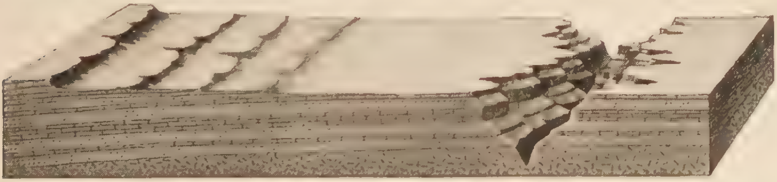


FIG. 73. — A generalized block diagram of the Grand Canyon of the Colorado. The youthful stage of the region is shown in the fact that the streams have as yet accomplished but a small part of the work to be done. The Colorado valley is a young valley. The cliffs of the canyon are formed of resistant beds, while the slopes are of weaker beds.

One of the grandest canyons in the world is the Grand Canyon of the Colorado in Arizona (Fig. 73), which was formed under conditions most favorable for steep-sided valleys. The river flows through a high plateau, 6000 to 8000 feet above the sea, in which it has cut a trench a mile deep in certain places. The climate is arid; the gradient of the valley is steep; the amount of sediment is sufficient to furnish tools for cutting, but not so great as to overload the stream; the rocks are sandstones, limestones, and shales, overlying granite. The Grand Canyon in Arizona is about 220 miles long and may be described as a valley within a valley, since, in certain localities, the upper portion, cut in the softer, sedimentary rocks, is eight to ten miles wide, while the lowest part cut in the hard granite is barely wide enough to hold the river. The total depth of the canyon is almost a mile. The canyons of the tributary streams branch again and again as they are followed back, and are miniatures of the Grand Canyon.

FIG. 74. — Ausable Chasm, Chazy, New York. This is a young valley. (U. S. Geol. Surv.)

The gorge of the Niagara River, Ausable Chasm, and Watkins Glen, in New York, are examples of canyons developed in a moist region. In these cases the valleys are all postglacial and have been cut so rapidly that their sides have been but little widened by the weather. In Ausable Chasm (Fig. 74) the verticality of the walls has been maintained in places by vertical joints.

Instances of Rapid Erosion. — The Duna, a river of eastern Prussia, blocked by an ice jam in 1901, was forced to take a new course. In thirty-four hours it was able to cut a gorge one meter to three and a half meters deep and four meters to eight meters wide, representing an excavation of 2250 cubic meters of material. The bottom of the Sill tunnel in Austria was provided with a pavement of granite slabs more than a yard thick. Great quantities of débris were swept over this pavement at a high velocity, and so rapid was the abrasion that it was found necessary to renew the granite slabs after a single year.

Effect of Deforestation on Rivers. — When forests are cut down or the vegetation on the hills is killed, the latter being sometimes the case in the vicinity of smelters, erosion may be very rapid. This is well shown in Potato Creek (Figs. 75, 76) in the Ducktown copper region of Tennessee, where the waste from the bare slopes is too great for the stream to remove and is piled up along its course as a flood plain (p. 119). In this creek the waste has accumulated for a number of years at the rate of a foot or more a year (Fig. 76, *A*, *B*), and has built up a flood plain in which telephone poles are buried almost to their cross arms, while highway bridges and roadbeds have been either buried or swept away by floods.

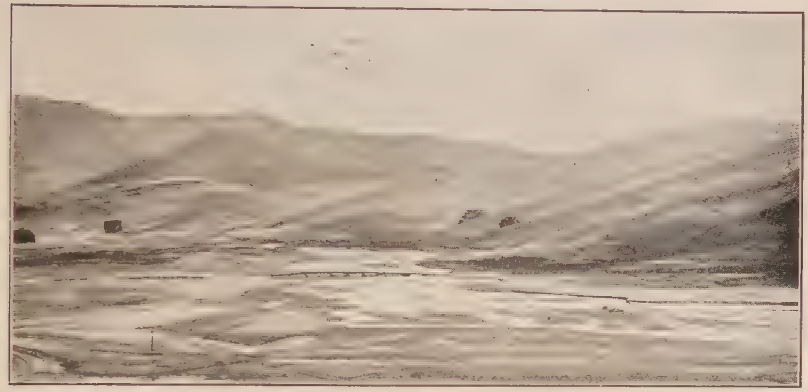


FIG. 75. — Potato Creek, Tennessee, a stream overburdened with waste and aggrading. (See also Fig. 76.) (U. S. Geol. Surv.)

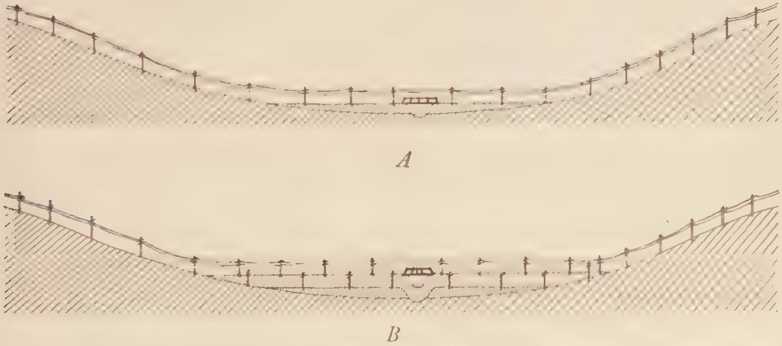


FIG. 76. — Generalized diagram showing the effect of deforestation on Potato Creek, Tennessee. *A* shows the former condition of the valley, and *B* the condition after the timber had been killed and the stream loaded with sediment. The telephone poles were buried to their cross arms. (Modified after L. C. Glenn.)

Fig. 77. — Rapid erosion of deforested land and one method of preventing further erosion. (U. S. Geol. Surv.)

The effect on stream flow of forested and deforested (Fig. 77) areas is well illustrated near Biltmore, North Carolina. The Davidson River has its upper drainage basin in the Pisgah forest; the Tuckasegee River in a deforested land that has been logged, burned over, pastured and farmed. The two areas drained are of geologically the same age and structure; the headwaters of the streams are found within the same range of mountains; the rainfall of the two areas is the same; the steepness of slope of the two watersheds is about the same. Yet the Tuckasegee, though the larger river, shows greater fluctuation in discharge than the Davidson; and the Davidson is practically free from sediment, while the Tuckasegee bears gravel and sand which it often spreads over fertile lands.

Fig. 78. — A young valley, western Nebraska. The work of the stream has only begun.

Growth of Valleys. — It is possible to study the growth of a valley in almost any region. Water does not flow down a slope in sheets for long distances, but soon finds depressions where it accumulates into streams. Even though a slope were perfectly uniform, a slight heterogeneity of soil or rock would permit the water to remove more material in one place than in another and thus begin the excavation first of a gully, and later, by prolonged erosion, of a ravine which still later would develop into a broad valley.

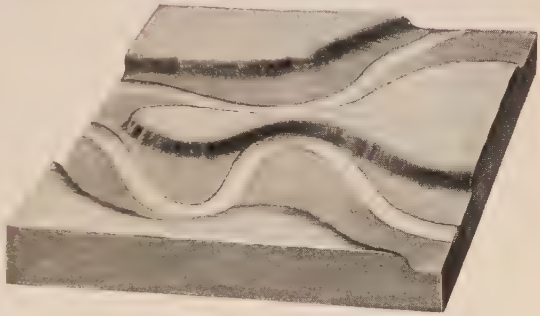


FIG. 79. — Block diagram showing the manner in which the divide between two streams is narrowed.

A valley is lengthened at its upper end and is cut back by the water which flows in at its head (Fig. 78), the direction being determined by the greatest volume of water which enters it. This is called *headward erosion.* A valley is widened by rainwash, lateral erosion (Fig. 79), and in other ways (p. 89). Its length depends upon the distance to which its stream can cut inland. At the beginning a valley has running water only during and immediately after rains, but later, when it has cut below the water table (p. 56), a permanent stream flows through it (Fig. 32, p. 57). Tributary streams tend to turn in the direction of their main (Fig 80), a feature which is often most pronounced late in their history.

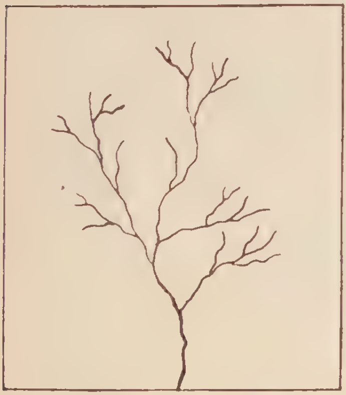


FIG. 80. — Map showing the usual relation of tributary streams to the main stream into which they flow.

Valleys Formed in Ways Other than by Stream Erosion. — Although the great majority of valleys are developed by stream erosion, some were already formed for the streams which flow through them. The popular notion that canyons, such as that of the Colorado River in Arizona, were formed by great cataclysms which rent the earth and produced the deep fissures now occupied by streams, is without foundation. Streams, however, do occasionally flow into fissures formed by the fracturing of the surface during earthquakes, but they are so few as to be unimportant. Some great valleys, nevertheless, were ready made for the rivers which flow through them. The Great Valley of California, through which the San Joaquin and Sacramento rivers flow, was formed, not by stream erosion, but by the sinking of the land along a valley-like depression, or by the uplift of parallel mountain folds, and is called a *structural valley*. Into such a depression streams may flow from the high lands on the sides and unite (unless the region is arid) to form a river system. The Great Basin region of Utah is also a structural valley, but because of the aridity of the climate no streams flow through it. The River Jordan and the Dead Sea are in a valley formed by the sinking (faulting, p. 261) of a long and comparatively narrow block of the earth's crust. Such a valley is called a *rift valley*. Owen's valley in California and a portion of the Rhine valley in Germany (Fig. 81) are other examples of valleys due to faulting. Glaciers excavate valleys in the solid rock, which may afterwards become occupied by streams, but these are usually merely

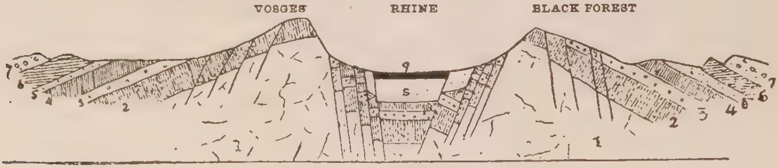


FIG. 81. — Section across the Vosges and Black Forest, Germany, showing the graben in which the Rhine flows. (Penck.)

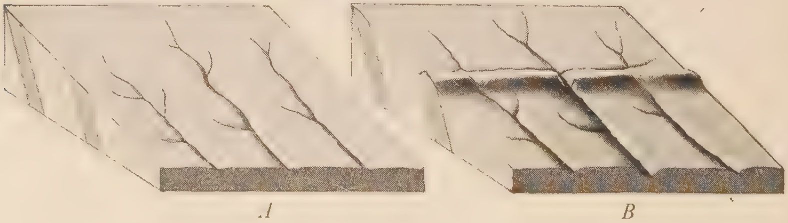


FIG. 82. — Diagram *A* illustrates the development of parallel consequent streams on a sloping surface. Diagram *B* is the same region after the streams have become adjusted to the structure of the underlying rocks. The streams entering the main at right angles are subsequent streams. The main stream flows through its water gap in the hard ridge. The gaps on either side were eroded by former streams but no longer have streams in them and are called wind gaps.

ancient river valleys which have been widened and deepened by the ice (p. 129).

Fig. 83. — Diagram *A* shows a region in which a stream flows at grade. Diagram *B* shows the same region after it has been slowly upwarped athwart the course of the stream. The river is shown as having been able to deepen its valley as rapidly as the elevation occurred. A stream with such a history is an antecedent stream, since it was able to maintain the course it had prior (antecedent) to the deformation of the surface.

The Direction of Valleys. — The direction of stream valleys depends upon a number of conditions, some of which can be illustrated by a hypothetical case. If a portion of the bottom of a shallow sea is raised above sea level, the land, under these conditions, will have no established stream valleys. When, then, the rain falls first upon such new land, it will gather in places where there are depressions and form large or small lakes. Elsewhere, rivulets will flow down the slope, joining here and there in their descent until a stream of considerable length develops. Streams of this sort, whose position and direction are determined by the slope of the original land surface, are called (1) *consequent* (Fig. 82 *A*), since their direction is a consequence of the topography of the country, without regard to the character of the rock through which they pass. The streams on the Atlantic Coastal Plain are chiefly consequent streams. As streams deepen and lengthen their valleys, their tributaries may encounter new kinds of material and find that some are more easily eroded than others, with the result that they gradually develop valleys in the less resistant rocks. In such case, the position and size of the branch streams are determined by the nature of the underlying rock and not by the original slope of the surface; the valleys being cut in the weaker strata, while the harder strata stand up as ridges or even mountains. The Shenandoah valley of Virginia, the Lehigh valley of Pennsylvania, and the Hoosic and Hoosatonic valleys of Massachusetts and Connecticut are examples of valleys of this type. Valleys formed in this way are called (2) *subsequent* (Fig. 82 *B*), the process being known as *structural adjustment*.

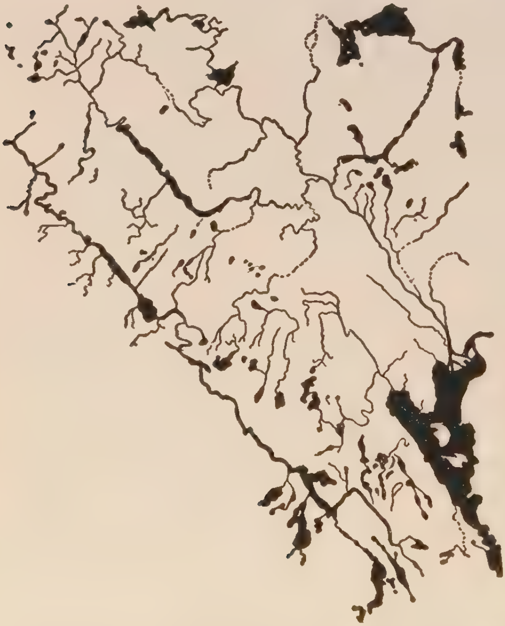


Fig. 84. — Direction of drainage determined chiefly by faulting and jointing, near Lake Temiskaming, Ontario. (After Hobbs.)

It will readily be seen that if streams drain adjoining regions, the one whose course is most generally confined to the more easily eroded beds will grow more rapidly and so may cut headward until it captures branches or even the entire upper courses of streams less favorably situated. Such a process is called *stream piracy* (p. 107). If the land is warped up athwart the course of a consequent stream whose direction is so well established that it is able to degrade its bed as rapidly as the elevation takes place, thus keeping its old course, the stream is called *antecedent* (Fig. 83 *A* and *B*).

(3) Another factor which sometimes determines the direction of a stream is faulting (p. 261) (Fig. 84). In regions of pronounced faulting, such as the Adirondacks, the courses of many streams may,

for considerable stretches, follow lines of dislocations. (4) Where the rock over which a stream flows is strongly jointed (Fig. 85), the joints are sometimes followed to some extent by the smaller tributaries. Larger streams, however, are less affected, usually showing little evidence of this influence. (5) When streams flow through structural valleys (p. 100), their direction is necessarily predetermined. (6) In a region underlain by horizontally bedded rock, the valleys extend in many directions without systematic arrangement and are described as *dendritic* (treelike). Such a river system is in striking contrast to one developed in a region of tilted strata in which the beds vary in their resistance to erosion. In such a region the tributaries have a trellised appearance (Fig. 92, p. 107).

Fig. 85. — Fall Creek, South Dakota. Showing the effect of jointing on the course of a stream.

Basins and Divides. — All the land surface which is drained by a river and its tributaries is called its *hydrographical* or *drainage basin*, and the boundary between two river basins is termed the *divide*, since the water falling on it is divided, part flowing into one river system and part into the other. A part of the Great Continental Divide, which separates the basin of the Mississippi River which empties into the Gulf of Mexico and that of the Snake River which finally discharges its waters into the Pacific Ocean, is in the Yellowstone National Park. A divide may be a sharp ridge, as, for example, in the Kicking Horse River basin of British Columbia, where the divides between the tributaries have been worn down to knifelike ridges which in many places are not a foot in width; or a flat plain, so level that the location of the divide is uncertain. Such a divide is the *height of land* between the Great Lakes and Hudson Bay, where the same swamp often drains both north and south. The position of the divide between the Orinoco and Amazon rivers in South America is, perhaps, even more uncertain. Divides are seldom stationary, since the streams on the opposite sides do not usually cut headward or laterally with equal rapidity. The divide between two tributaries of the same river may also be narrowed by the lateral erosion of the streams until it disappears (Fig. 79). By an increase in the number of tributaries, ridges are cut into hills. In this way the Seven Hills of Rome were sculptured, and many of the conspicuous buttes of the western United States (p. 328) were separated from the higher plains (Figs. 86, 87).

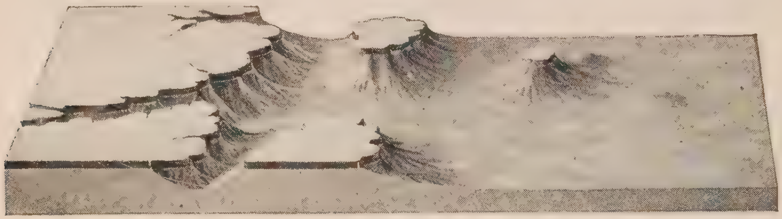


Fig. 86. — Block diagram illustrating the formation of outliers and the erosion of a plateau. The fronts of the High Plains in Nebraska and elsewhere are being cut back in this way.

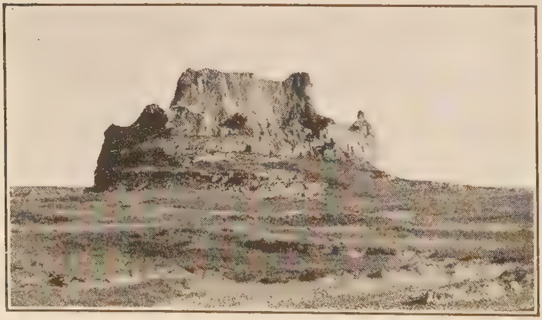


Fig. 87. — Eagle Rock, Nebraska. (U. S. Geol. Surv.)

Elevations Due to Unequal Hardness. — The term *hogback* is given to narrow ridges which stand above the general level of a region, because of the greater resistance of a steeply dipping layer of rock and of the greater erosion of the softer rock (Fig. 88 *A*, *B*). They are especially conspicuous on the flanks of mountains. When regions in which the rocks are folded have been subjected to erosion the harder beds stand up as mountain ridges. In this way the Appalachian Mountains (p. 477) were formed. The difference between a hogback and such mountains is largely one of height, width, and extent.

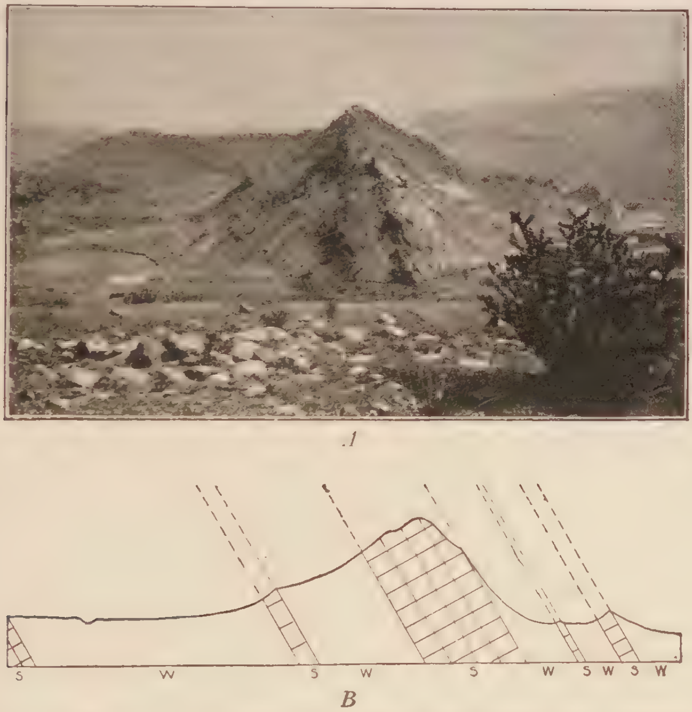


Fig. 88. — Photograph and section of a hogback near Cañon City, Colorado. The ridge is due to the superior strength of one main and two subordinate strata. *SS* are strong and *WW* weak rocks. (Modified after Brigham.)

Where sheets of lava cover softer beds, as is not uncommon in the southwestern portion of the United States, flat-topped, isolated hills, called *mesas* or tables (Fig. 89), are formed by the headward cutting of tributary streams. Any harder bed of horizontal rock

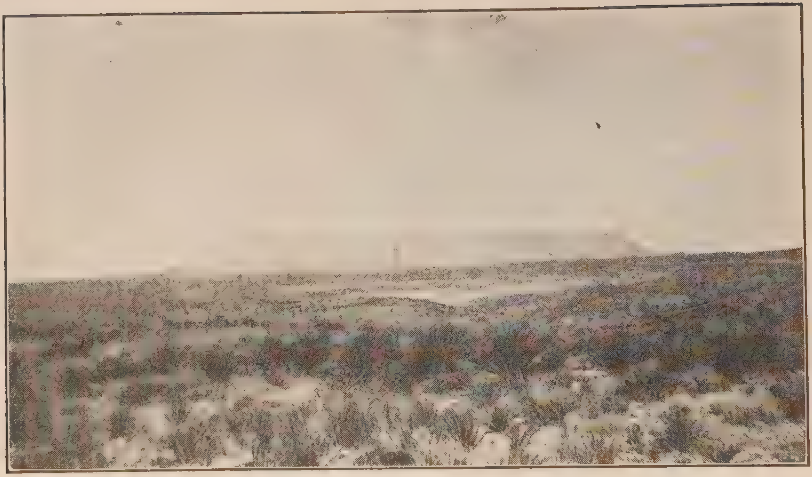


Fig. 89. — Black Mesa. (U. S. Geol. Surv.)

overlying softer beds will produce such hills, the name "mesa" being used to designate the shape of the hill, not the kind of rock. In the western United States the word *butte* is used for any steep-sided hill and is also loosely used for any conspicuous elevation.

Outliers. — When a part of a formation is separated from the main body by erosion (or, occasionally, by faulting), it is called an *outlier* (Fig. 90). It is, therefore, simply a remnant of a more extensive bed or series of beds. Outliers are usually short-lived, since they are objects of attack on all sides by erosion. Outliers often occur scattered along the front of prominent escarpments; as, for example, near the border of the High Plains in the Middle West (Fig. 86).

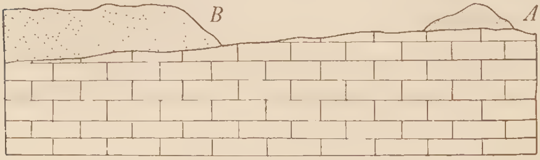


Fig. 90. — In the diagram outlier *A* was formerly united to *B*, but was separated from it by erosion.

Rock Terraces. — In a region underlain by alternate hard and soft beds, such as in the Colorado Plateau, the resistant rocks may form *rock terraces* and the softer rocks slopes in the river valley or canyon. The "steps" or "benches" of the walls of the Grand Canyon of the Colorado (Fig. 73, p. 95) are among the most striking features of this remarkable valley. Rock terraces may also result from the elevation of the land, since when the gradient of a river is increased it is able to cut a gorge in its old valley floor, leaving rock terraces on the two sides.

Stream Piracy. — Because of the more rapid headward cutting of one stream than another there is a continual though usually slow absorption of the tributaries of one river system by another and also a struggle for existence among the tributaries of each river system. A stream which has cut headward so rapidly as to divert the headwaters of another stream to itself is said to *behead* the latter, and the act is spoken of as *stream piracy* (Figs. 91, 92, 93).

FIG. 91. — One of three diagrams showing the development of topography in a region where the underlying strata are inclined (dip) and vary greatly in their resistance to erosion. The region is conceived to be reduced to a peneplain with low ridges of harder strata. (Modified after Davis.)

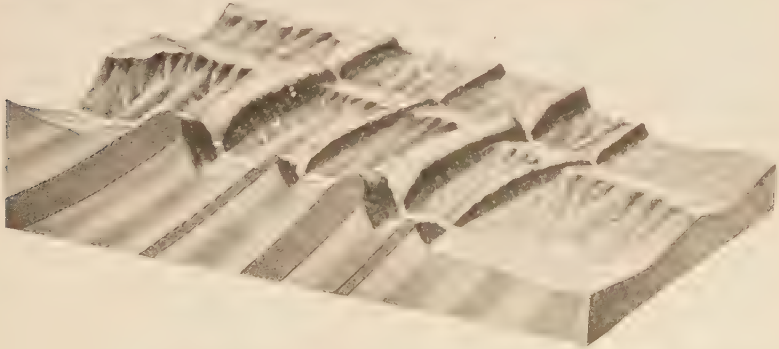


FIG. 92. — In this (second) diagram the peneplain has been elevated and the streams have cut deep valleys and picturesque water gaps. The direction of the tributary streams is determined by the strata, and a "trellised" drainage system results.

The result of stream piracy is well shown in the difficulties experienced by a commission appointed by the Argentine and Chilean governments to determine a disputed boundary in the Andes between the two republics. Since no map was available when the boundary was first fixed, this was stated as following the crest of the mountains, as it was believed that this was permanent and was identical with the divides between the Atlantic and Pacific rivers. Later a dispute arose as to the exact boundary, and the survey made to settle the question showed how inaccurate this belief was. It was found that the Chilean rivers, with their short, steep routes to the Pacific Ocean, had captured the upper courses of nearly all of the Argentine rivers, obliging them to make sudden turns and to flow through the deep gorges which lead to the Chilean coast. Another example of stream piracy is to be seen in the Kaaterskill Creek of New York, which, because of its shorter course to the Hudson, has captured the lakes at the headwaters of the Schoharie Creek which flows on a gentle gradient by a circuitous route to the Mohawk River. Many of the "wind gaps" (passes without streams flowing through them) of the Blue Ridge in Virginia were eroded by streams flowing to the sea, whose headwaters were captured by other streams which, although following longer courses, were able, because of their greater volume of water, to deepen their valleys more rapidly than those flowing through these gaps. The Cumberland Gap, through which passed many thousands of the early immigrants to Kentucky, has such a history.

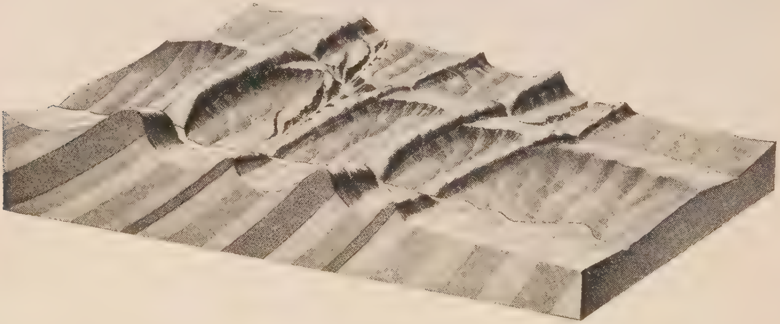


Fig. 93. — In this (third) diagram some of the subsequent streams are seen to have cut back until they have captured part of the drainage of the parallel, consequent streams, leaving wind gaps. When this region is reduced to base level it may again have the appearance shown in Fig. 91. (Modified after Davis.)

Conditions favorable for river capture occur in regions of tilted beds (Figs. 91–93) in which there is a marked difference in the strength of the rocks. The larger branches follow the outcrops of the weaker beds, and their tributaries join them at right angles, because all except the master streams are subsequent rivers (p. 102). In such regions, the larger streams cut rapidly in the weaker rocks and often behead the streams that flow across the hard beds. After a stream has been captured its new grade will be steeper than before, and it is likely to cut a trench in its old valley, leaving the remnants of the latter as terraces. In regions of horizontal rocks stream capture is also common. If one of two streams heading toward the same point has a straighter and steeper course, or a greater volume of water, or a load of sediment sufficient for rapid cutting but not so great as to cause deposition, it may cut back more rapidly than the other and in time capture the headwaters of the latter.

The Erosion Cycle

The terms *youth*, *maturity*, and *old age* are used to express the characteristics of valleys, and are helpful since they are as descriptive of them as the same terms applied to human beings. "They have reference not so much to the length of their history in years as to the amount of work which streams have accomplished in comparison with what they have before them."

Youth. — Young valleys are V-shaped, with steep sides, and are occupied by rapid streams unless the land is low. Since they have had but a short life, rapids and waterfalls are often numerous; the divides are wide and ill-drained, as the frequent occurrence of marshes and lakes usually indicates. The Grand Canyon of the Colorado, the steep gorge of the Niagara River, and all narrow, steep-sided, or V-shaped valleys are in youth. A *region* is said to be youthful (Fig. 94) when sufficient time has not elapsed for streams thoroughly to dissect and drain it; in other words, *the streams have the larger part of their task before them*. The Red River valley of North Dakota and Minnesota is such a region, since it has not long been

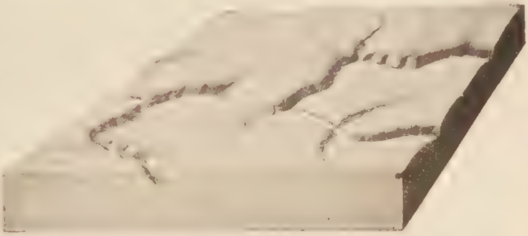


Fig. 94. Block diagram showing a region in the youthful stage of its erosion cycle. Sea level is represented by the bottom of the diagram.

subjected to stream erosion. It was formerly the site of a lake (p. 656) whose bed was covered evenly with sediment. After the lake was drained the bed was exposed to erosion, and a drainage system was developed whose stream courses were determined by the inequalities of the bottom. Later in its history new tributaries will erode side valleys, the main valleys will be widened, and a mature topography will result.

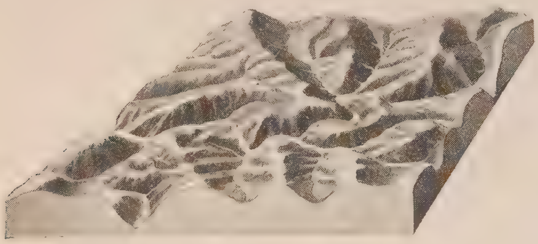


Fig. 95. — Block diagram showing a region in the mature stage of its erosion cycle. The bottom of the block is sea level.

Maturity. — A mature valley is deep, but has flaring sides and gently rounded upper slopes. A region in full maturity (Figs. 95, 96) is in decided contrast to a youthful region. Instead of few tributaries and consequently wide divides, the land is thoroughly dissected by valleys, the divides are narrow, the valley sides are less steep than in youth, and the streams are accomplishing their greatest work both in erosion and transportation. In such a region the rainfall runs almost immediately into the streams; lakes have practically disappeared, having been drained by the cutting down of their outlets or filled by stream sediment and organic matter. In this stage the relief is greatest, and arable land is at a minimum; roads are difficult and must follow either the valleys or the narrow divides, and the

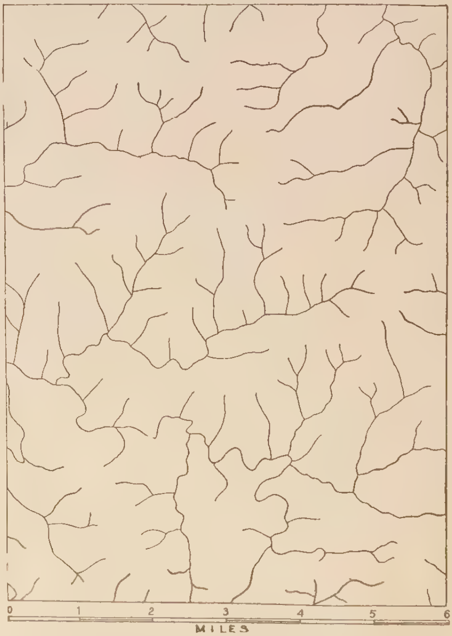


Fig. 96. — Map showing the stream courses in a mature region.

inhabitants are isolated. There are many such regions in the United States; for example, large portions of West Virginia, southeastern Ohio, eastern Kentucky, and Tennessee are in maturity. As a rule a master stream reaches maturity earlier than its tributaries, and in its lower course earlier than in its upper course. A region in maturity may be traversed by a stream which flows through a broad, *old* valley, and a youthful region may be traversed by a mature stream.

Old Age. — Continued erosion will gradually cut down the valley sides (Fig. 97) to gentle slopes, lower the divides, and thus tend to reduce the surface to an undulating plain. The sluggish streams will meander (p. 121) in wide valleys. The region is then in *old age* (Figs. 98, 91). An absolute plain may, perhaps, never be reached, since elevations will be left here and there because of some favoring condition, such as (1) hardness of rock or (2) a favoring position with reference to the drainage of the plain. Such hills or mountains rising above the general level of the surface are called *monadnocks*, from a mountain of that type in New Hampshire. Portions of Kansas have passed through youth and maturity and are now in the stage of old age.

Fig. 97. — Diagram showing the profile of young, mature, and old valleys.

Fig. 98. — Block diagram showing a region in old age. Sea level is represented by the bottom of the block.

The time required for the production of a base-leveled condition or for "peneplanation" is called the *cycle of erosion.* It will take, perhaps, one hundred thousand times as long to pass from maturity to old age as from youth to maturity. It will be seen from the above that the age of a region is not recorded in years but in the work accomplished or to be accomplished.

Effect of Elevation and Depression on Streams. — If a region is elevated after it has been reduced to base level (peneplain), the streams will be quickened and will again be enabled to deepen their valleys. If the streams meandered (p. 121) on the peneplains, they may intrench themselves in their old courses until they flow through deep, meandering rock gorges. When a stream has thus intrenched its meanders, the evidence is strong that it has been rejuvenated. Many examples of intrenched meanders are to be seen in Europe and in the United States. In the latter, Pennsylvania, Kentucky, and Utah furnish excellent and striking examples. The great natural bridges of Utah, one of which has a height of 305 feet and a span of 273 feet, were formed by the perforation of the necks of intrenched meanders, as was also that of the Ardèche River, France (Fig. 99).

Fig. 99. — Map showing the course of the Ardèche River, France. The origin of the natural bridge by the perforation of the neck of the meander is evident.

If a region is uplifted before the erosion cycle is completed, the rivers will deepen their courses, leaving their former broad flood plains (p. 128) standing as terraces or " benches." A section of such a valley will show a valley within a valley. If a region is more elevated near the ocean than further inland, the upper courses of the streams will be " ponded," unless they are able to deepen their valleys as rapidly as the land is elevated. This differential movement of the earth's surface is called *warping*. Streams which hold their courses in spite of differential elevations, as has been seen (p. 102), are called antecedent streams.

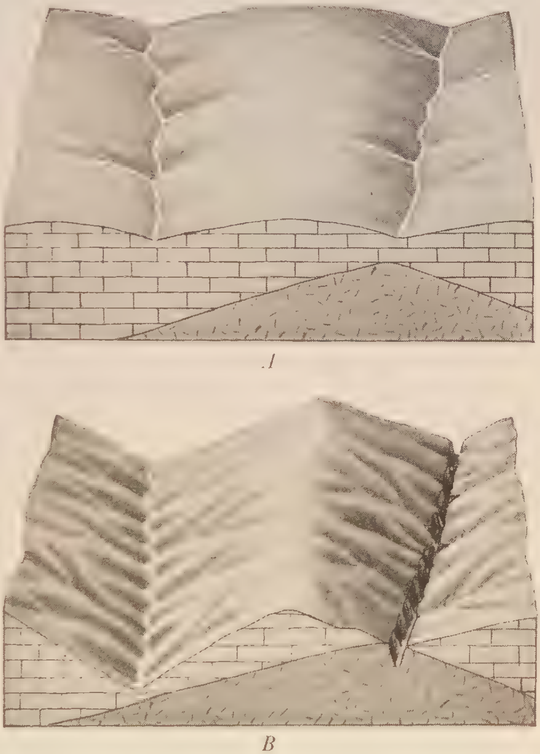


Fig. 100. – Two block diagrams showing the effect of erosion upon resistant and weak rocks. The streams in *A* have approximately the same slope and are deepening their valleys in strata of the same kind. *B* shows that the stream on the right encountered resistant granite which was both eroded and weathered more slowly than the weaker rock. As a consequence, the stream on the right has cut a deep and steep-sided gorge, while that on the left has cut a broad valley with gently sloping sides.

If a region underlain by tilted rocks which vary in composition, some resisting erosion more than others, is reduced to base level and then raised, the subsequent erosion is such as to give certain proof of its earlier history. An interesting example, in which, however, the river encountered granite (Fig. 100 *A* and *B*) rather than tilted rock, is found in the history of the Gunnison River in Colorado. When the Rocky Mountains were being uplifted to their present position, the streams which now drain them began to cut their valleys. Among them the Gunnison River followed along a depression of the plateau and began to deepen its bed. Its course happened to lie over a great mass of granite, buried beneath softer strata. The river, having a steep gradient, rapidly cut its way through the soft surface rocks and finally encountered the granite. Since its valley was already deep when this occurred, it was unable to turn aside from the hard rock and continued to cut its way through it until the picturesque Black

Canyon, more than 2000 feet deep, was excavated. The Uncompahgre River, which joins the Gunnison after flowing in approximately the same direction for some distance, was born at the same time. It has flowed, however, over soft material which could be readily eroded, and has been able to excavate a valley several miles in width which in one place is separated from the narrow Black Canyon by a narrow ridge of granite.

If a region is depressed, the velocity of the streams will be lessened, and the condition of old age will be hastened. Drowned river valleys (p. 227), such as the Delaware, the St. Lawrence, and Chesapeake Bay (Fig. 101), are the result of the sinking of the land in the lower courses of the rivers.

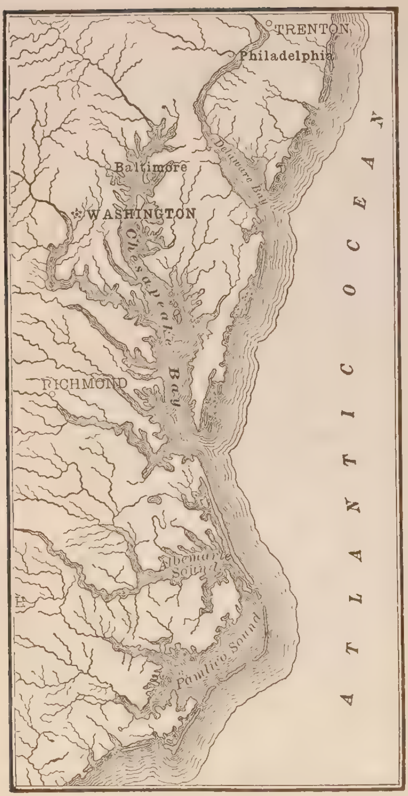


FIG. 101. — Drowned river valleys. Chesapeake and Delaware bays and Albemarle Sound were formed by a lowering of the land which permitted the sea to fill the valleys.

PENEPLANATION

When a *base-leveled* region (peneplain) has later been uplifted and dissected by erosion, the evidence of the former base-leveled condition is to be seen in the horizontal sky line presented by the higher hills (Fig. 102). The effect of erosion on an elevated peneplain under different conditions of rock structure is shown by a study of (1) southern New England, (2) the Appalachian region, and (3) eastern Canada.

(1) **The Peneplain of Southern New England.** — Southern New England is underlain on each side of the broad Connecticut valley by hard, crystalline rocks; the valley is in part composed of sandstone and in part of lava. Before the present elevation took place, erosion had been active for so long that even the lavas, granites,

FIG. 102. — The peneplain of the Rhine district near St. Goar, in which the Rhine has cut a shallow valley. (Photo. D. W. Johnson.)

gneisses, and schists had been cut down to a comparatively level plain, above which stood some hills a few hundred feet high, such as Mt. Monadnock, Mt. Greylock, and Mt. Wachusett. When this peneplain was raised and the streams again began to erode, the weak sandstones were quickly cut away, leaving the trap rocks standing as the Holyoke and other trap ranges of the Connecticut valley, and the old crystalline rocks bounding the "valley" as the highlands. In the highlands, streams have cut deep and usually narrow valleys. The higher hills have about the same altitude, except that the surface of the ancient peneplain rises to the northwest; on Long Island it is at sea level, but its height increases to an altitude of about 1500 to 2000 feet in Vermont and New Hampshire. Mt.

FIG. 103. — Peneplain with several monadnocks in the distance. Near Camp Douglas, Wisconsin. (Sankowsky.)

Monadnock, Mt. Greylock, Mt. Wachusett, and some others, as has been stated, rise as monadnocks (Fig. 103) several hundred feet above the ancient plain.

(2) **The Appalachian Peneplain.** — The Appalachian Mountain region, from the Hudson River to Alabama, is underlain by rocks differing in their resistance to erosion, which have been bent into broad folds and, in places, broken by faults (p. 25) (Fig. 104). In ancient times (Cretaceous, p. 516) the folds were planed off by erosion, leaving the outcropping strata in long, more or less parallel lines, resistant beds alternating with weaker ones. The surface of this (Cretaceous) peneplain is now seen in the approximately level crests of the ridges, showing that the base-leveling of the region had been almost completed. Upon this plain the rivers took their courses to the sea: the Delaware, Susquehanna, and Potomac flowing to the Atlantic across the strata without regard to their structure; the New River of Virginia and the French Broad of North Carolina flowing to the west; while the southern part of the region was drained to the south by the large Appalachian River. An upwarping along a north-south axis occurred which diminished the velocity of some streams and increased that of others, thus favoring stream capture (p. 108). The Potomac, Susquehanna, and Delaware rivers, continuing to flow in approximately their old channels, cut the deep gorges or *water gaps* at Harpers Ferry, the Delaware Water Gap, and near Harrisburg. The tributaries of these rivers, such as the Shenandoah and Lehigh, cutting more rapidly in the weaker limestone beds, have excavated broad, *subsequent valleys*, more or less at right angles to their mains, leaving the resistant strata standing up as mountains (Fig. 105). The gradient of the southwestward, as well as that of the eastward-flowing streams was increased and resulted in the headward cutting of one of these until it captured the headwaters of the southward-flowing Appalachian River. A later warping in northern Alabama and Mississippi along an east-west line caused a tributary of the Ohio to cut headward and capture the stream which had formerly robbed the Appalachian

Fig. 104. — A generalized section across the southern Appalachian Mountains. Peneplains are shown by the dotted lines.

River. In this way the Tennessee originated, made up of parts of three rivers which formerly had different courses.

After the first elevation, the region remained at approximately the same level for a long time, as is shown by the accordant altitudes of the plainlike valleys between the mountains, but long before the ridges could be reduced, another uplift (Fig. 104) occurred which caused the streams to deepen their beds to the present level. The last uplift must have been relatively recent, since the new valleys are as yet comparatively narrow.

FIG. 105. — The Water Gap near Harrisburg, Pennsylvania. The horizontal sky line shows the surface of the ancient peneplain. (Maryland Geol. Surv.)

(3) **The Laurentian Peneplain.** — The great hunting and fishing region of North America is that vast area, almost surrounding Hudson Bay, which stretches from Lake Superior and the St. Lawrence River on the south to the Arctic Ocean on the north, and from the shores of Labrador on the east to Lake Winnipeg on the west. This is known as the "Laurentian shield" (p. 389). When an observer stands on almost any eminence in this region, he finds that he is on a great

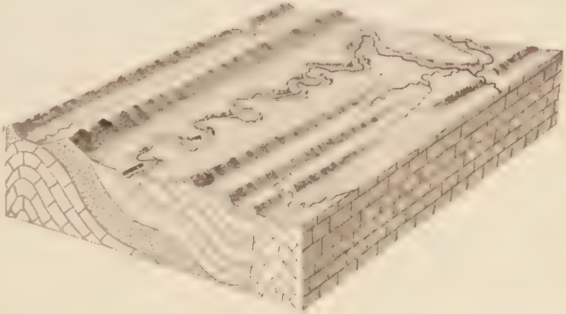


FIG. 106. — A block diagram of a part of the Appalachians, showing two peneplains, intrenched meanders, and a water gap. (Modified after Lobeck.)

plain dotted with lakes, in which, especially along the margins, the streams flow through deep valleys over falls and rapids. The ruggedness of the southeastern margin of the peneplain, where it borders the St. Lawrence, is due to the many valleys which have been cut in it and which have given rise to the rough region known as the Laurentian Mountains. The complicated and distorted rocks of the region vary greatly in composition, but have, nevertheless, been reduced to a common level, with the exception of the residual domes and ridges (monadnocks) of the peneplain. The interior peninsula of Labrador is so level that in an area of 200,000 square miles there is not a difference of general level of more than 300 or 400 feet. "The Canadian shield can be described as an ancient peneplain which has undergone differential elevation; has been denuded, and subsequently slightly incised around the uplifted margin." (Wilson.)

The Adirondacks were in part reduced to base level at the same time, but in the eastern portion either the surface was not base-leveled, or subsequent movements have raised it and given it varying altitudes.

Rate of the Denudation of Continents. — The land surface of the United States is being lowered at an average rate of about one inch in 760 years, or of one foot in a little more than 9000 years. The total amount carried to the sea each year from the United States is approximately 270,000,000 tons of dissolved matter and 513,000,000 tons of suspended matter. "If this erosive action had been concentrated upon the Isthmus of Panama at the time of the American occupation, it would have excavated the prism for an eighty-five foot level canal in about seventy-three days." [1]

How the Load of Streams is Measured. — Estimates such as the above are obtained by measuring the amount of water discharged by rivers, together with the minerals in solution and the insoluble silt, and pebbles which are either carried in suspension or rolled along the bottom. The volume of water discharged by a river is found by multiplying the number of square feet in its cross section by the velocity a second to obtain the discharge a second. The quantity of silt is found by filtering samples of water from various portions of the section at different times of the year, and the quantity of soluble material is determined by evaporating samples of the water after filtering. The difficulty in obtaining accurate results is due to the

---

[1] U. S. Water-Supply Paper No. 234, p. 83.

fact that the velocity and volume of rivers fluctuate often from day to day, and the quantity of silt varies with the velocity. Moreover, the material in solution in a cubic foot is greater at low than at high water, since the proportion of spring water is then greater. It is also difficult to measure the quantity of material rolled along the bottom. It is believed, however, that notwithstanding these difficulties, the estimate of the rate of denudation of the United States of one foot in about 9000 years is accurate within 20 per cent.

Deposition

Causes of Deposition. — Streams bearing a full load will deposit their sediment when their velocities are diminished. (1) A stream flowing from a steep to a gentle gradient will deposit its coarser sediment. (2) When a stream emerging from a straight, narrow channel flows into a wide, winding one, its current is diminished by friction with its bottom and sides, and deposition may take place. (3) When tributary streams with steep gradients flow into slow-moving main streams, they may deposit a part of their load. (4) Since the velocity of a stream increases with its volume, it is evident that, if the volume is diminished in any way, as by seepage or evaporation, its ability to carry sediment will be correspondingly decreased. Consequently, rivers in arid regions are often depositing streams (p. 81), even when they have steep gradients. (5) When slow-moving streams, carrying much fine sediment, meet any obstruction, such as a stranded log or a tree which has fallen from the bank, the slight check to the current produced in this way may cause the formation of a sand bar or island. Many of the islands of the lower Mississippi River began as "snags." (6) When a stream reaches a body of still water, either a large lake or the ocean, all of the sediment soon finds a resting place. The goal of all sediment is the sea, but in its journey oceanward it makes many halts, forming the alluvium of the river valley.

Flood Plains. — Flood plains are formed by graded streams, as a result of both lateral erosion and of deposition during overflow. A broad, flat valley may be formed in this way. Since rivers normally first reach base level where they enter the sea, their flood plains are usually widest there. The lower Mississippi flood plain (which is, perhaps, more correctly described as a delta) is five to eight miles wide and is bounded on the east by clay bluffs 100 to 300 feet high, and on the west side, as far as the Red River, by less prominent banks. The downstream slope of a flood plain varies with the volume of the water in the stream and its load. The slope of the flood plain of the lower Mississippi, for example, is only two to three inches a mile, while streams carrying coarse material may build up flood plains with slopes of 50 to 75 feet to the mile. Flood plains are highest near the river and slope gradually away from it (Fig. 107). This is due to the fact that, at flood, the coarser and more abundant material is deposited where the silt-laden main current is checked by contact with the slow-moving waters of the sides.

FIG. 107. — The flood plain of a river. The natural levees on each side are shown, as is also the structure of flood-plain deposits.

FIG. 108. — Meanders, Owens valley, California. (U. S. Geol. Surv.)

The fertility of the Nile valley in Egypt is due to the thin layer of silt which is spread over the flood plain each year. If the sediment deposited on a flood plain is coarse, the plain will be infertile.

Meanders. — After a river has become more sluggish and is consequently unable to cut downward, it may undercut its banks on the outside of its curves and thus widen its valley floor. As the outside of a curve is cut away, the inside is filled with sediment to flood level, and a strip of land is thus formed. In this way, as well as by deposition during overflow, a broad, flat valley is developed which, as has been said, is called a flood plain because covered by water during floods. On such a flood plain a river will take a still more winding or meandering course (Fig. 108). The origin of these *meanders* is easily conjectured. Imagine a perfectly straight stream flowing through a level alluvial plain. If, under such conditions, a tree is blown over into the stream, a rock falls from the bank, or a tributary stream forces the current against the opposite bank, or brings in gravel and builds a natural jetty, the current will be deflected a little, the bank will be undercut, and the channel changed at this point (Fig. 109). The stream will then strike the opposite bank obliquely a little further down its course, wearing it away at this point, and thus, one after another, new meanders will be formed. A single obstruction may, therefore, affect the oscillations of the current for an indefinite distance down its course. The length of the Mississippi River (Fig. 110), from the mouth of the Ohio to the Gulf of Mexico, is 1000 miles, so meandering is its course, although the direct distance is only 600 miles. One of the plans for improving the Mississippi is to straighten the channel by cutting off the curves.

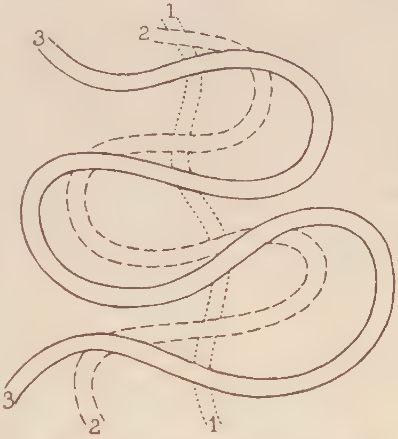


FIG. 109. — Diagram showing the initiation of meanders. (Modified after Salisbury.)

Oxbow Lakes. — Once initiated (Fig. 109), meanders tend to become more pronounced in form, changing from an open loop to one which is horseshoe-shaped. The neck of land separating one bend from the next may become more and more narrow (Fig. 111) until,

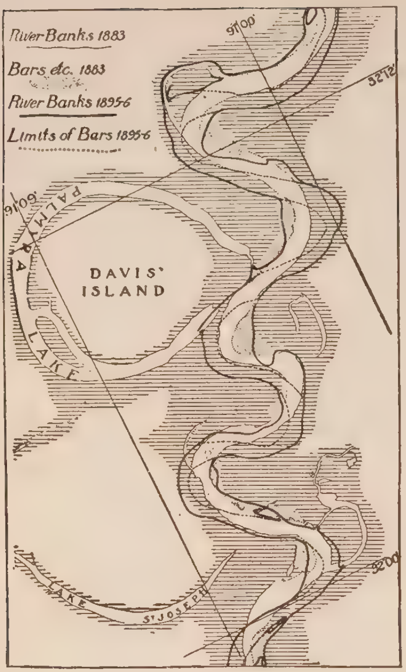


Fig. 110. — Meanders of the Mississippi River. The successive positions of the river in 1883, 1895, and later are shown. The movement of the meanders downstream and their tendency to increase are shown. (After Salisbury.)

in time of flood, the river may straighten its course by cutting a channel across this narrow strip, leaving *horseshoe* or *oxbow lakes*, or bayous, which are soon separated from the new and shorter channel by deposits of silt. Brooks tend to develop a greater number of bends than larger rivers, since they are easily deflected by accidental disturbances, such as a fallen tree or a landslide, while a larger river tends to obliterate its smaller irregularities and to develop the larger ones. As a result, we find many close-set meanders in small brooks, while in large rivers there are a small number of well-spaced meanders which grow to large size before they are cut off. Many examples might be cited of cities and villages located on the banks of meandering rivers, which have been left far inland by the cutting off of the meanders on which they were situated. Because of their changing channels rivers make very poor political boundaries.

In the course of time the "oxbow" lakes formed by the "cut-offs" are destroyed, as they are apt to be filled with sediment when the stream is at flood, and at other times sand is blown in by the wind, and vegetation takes root there.

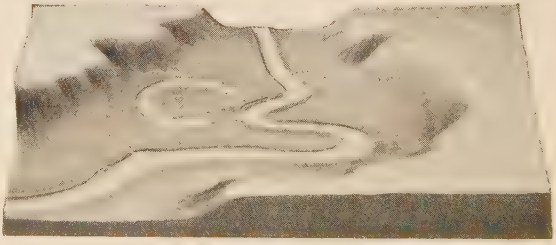


Fig. 111. — An oxbow lake formed by the cutting through of the neck of a meander.

Natural Levees. — A study of a topographic map of the lower Mississippi River shows that it flows between banks which rise ten or more feet above the surrounding swamps, and occasionally constitute the only dry land for long distances. Such embankments are called *natural levees* (Fig. 107). They are gradually built up in time of flood when the water is swift and contains much sediment. The current in the channel is sufficient to carry the sediment onward, but its velocity is checked where it comes in contact with the slow-moving flood water on the sides, sediment is deposited, and an embankment is thus erected above the swamp. Natural levees are often strengthened and heightened artificially to prevent floods, but it is readily seen that during a flood a river may break through its levees, spread over its swamps, and perhaps change its course. The Mississippi River broke through its levees in 1912, causing great destruction of life and property. The levees of the Hoang Ho in

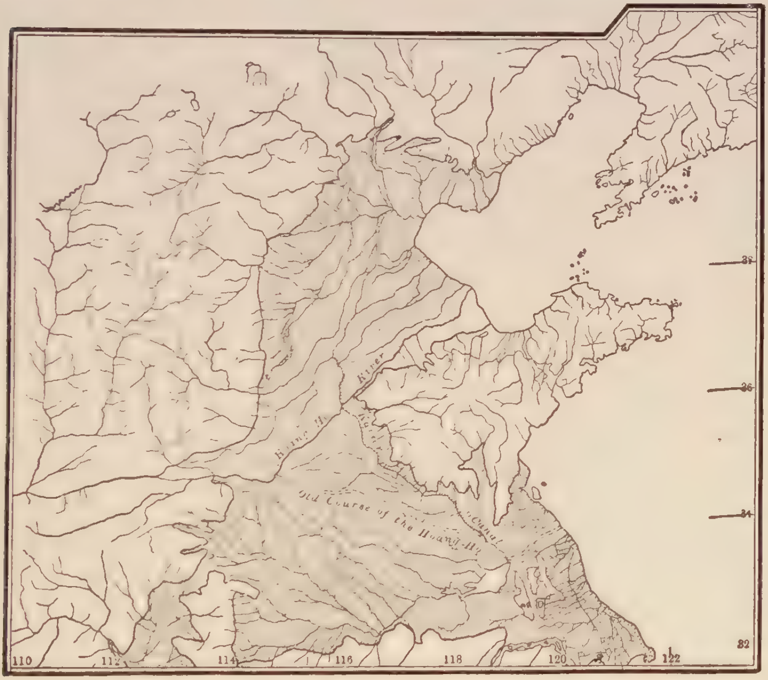


FIG. 112. — Map showing the changes in the course of the Hoang Ho (or Hwang River) on its delta (shaded). Its waters are restrained only by an elaborate system of dikes and canals. (Richtofen.)

China have been increased artificially so that, in places, the surface of the river is 30 feet above the surrounding plain, but in spite of man's efforts it has often changed its course and is called "China's Sorrow" because of its great destructiveness (Fig. 112). In 1904 the mouth was 250 miles north of its position 40 years before (p. 133).

Natural levees are sometimes high enough to turn the courses of the tributary streams for long distances; thus the Yazoo travels for 200 miles parallel to the Mississippi before entering it, and the St. Francis for 100 miles. Lakes are sometimes formed when a stream in winding through a valley builds up its levees and thus incloses basins between them and the banks of the valley (Fig. 113).

FIG. 113. — Shallow basins formed as a result of the building of natural levees along the stream are filled at flood time with water from the stream and from the sides of the valley. (Minneapolis topographic sheet, U. S. Geol. Surv.)

Alluvial Cones and Fans. (1) *In Arid Regions.* — In desert regions streams are fed chiefly by tributaries whose sources are in the mountains where the rainfall is greater than on the arid plains. At rare intervals heavy downpours (cloud-bursts) may occur on the lower courses which, though often of only a few minutes' duration, may fill the valleys, producing torrents of great erosive power. But ordinarily such streams rapidly lose volume as they flow out on the thirsty land, as their lower courses are seldom fed by springs. During certain seasons, when the rainfall in the mountains is heavy, some desert rivers are a hundred miles longer than at other times. Streams flowing from high lands into deserts quickly drop their sediment at the mouths of their gorges, both because their gradients are diminished and because their velocity is decreased as water is lost

Fig. 114. — An alluvial fan near Salt Lake City. (U. S. Geol. Surv.)

by evaporation and by absorption into the porous soil. In this way a pile of waste is accumulated, half cone-shaped, with a base varying in diameter from a foot to forty or more miles. Accumulations such as this are called *alluvial cones* when steep, or *fans* (Fig. 114) when the slope is not great. In general they are composed of coarser materials at the apex and progressively finer ones toward the base, since a stream first drops the larger débris with which it is burdened when its velocity is checked. The streams flowing over alluvial cones or fans seldom have

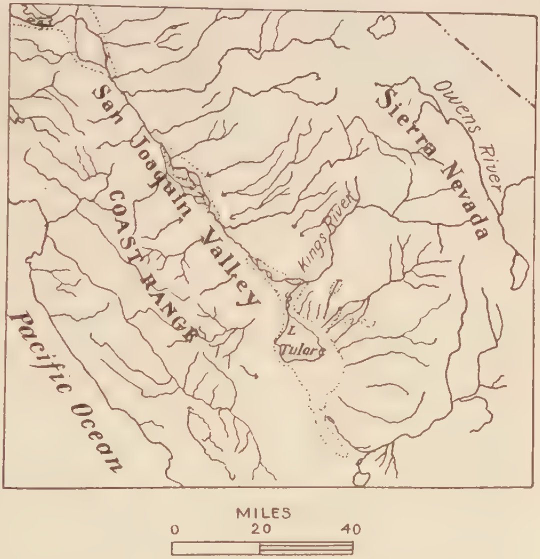


Fig. 115. — The San Joaquin valley and Tulare Lake, California. The basin of Tulare Lake is due chiefly to the building up of alluvial fans across the San Joaquin valley by Kings River and Los Gatos Creek.

single channels throughout their courses, because, as they lose volume, they are unable to carry all of their load and therefore deposit it along the sides of their channels, so narrowing them that the water breaks through the banks and forms other channels. This process may be repeated again and again until at the base of the cone a stream has been divided into a number of *distributaries.* These distributaries tend to keep the fan or cone symmetrical. The angle of the slope of these accumulations varies (1) with the rapidity with which the velocity of the stream is diminished; (2) with the kind and amount of the sediment; and (3) with the size of the stream. The slope of cones and fans of large streams usually is less than that of small torrents, which may be as steep as from 5 to 15 degrees.

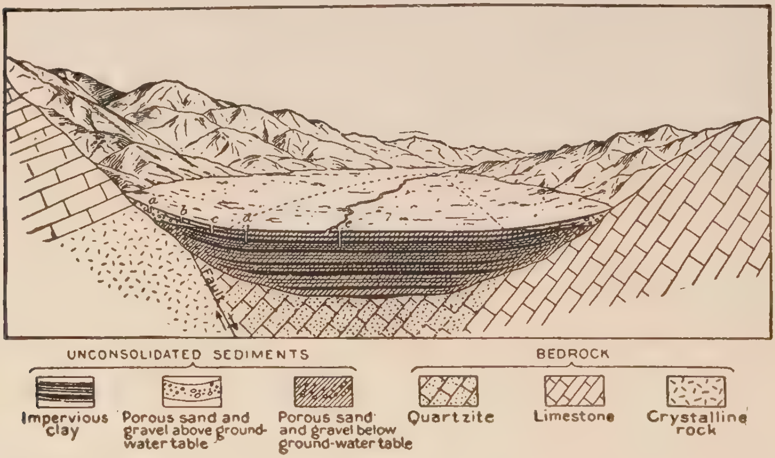


FIG. 116. — Cross section of a typical valley in an arid region. Beneath the alluvial slope gravel predominates, but towards the central flats it gives way to alternate layers of sand and clay. Water is obtained when wells reach the porous sediments, as at *c*, *d*, and *e*. The dotted line shows the base of the alluvial slope. (U. S. Geol. Surv.)

An alluvial fan sometimes causes the formation of a lake by building a dam across a river. Where Kings River enters the San Joaquin River of California it has deposited a fan which has dammed the San Joaquin, forming the shallow Tulare Lake (Fig. 115).

Piedmont or Alluvial Plains are formed by the coalescing of adjoining fans. The slope of such plains may be so uniform that the angle is not easily detected by the naked eye by one traveling over the region (Fig. 116). Almost any topographic map of a desert basin, however, shows that the slope of Piedmont plains is usually considerable.

In desert regions oases are often found on alluvial fans, since water can be obtained here from wells or from the mountain streams. The principal settlements of Utah are on the alluvial slopes at the foot of the Wasatch Mountains, and many of the cities of Persia and Turkestan are situated on alluvial fans.

(2) *In Humid Regions.* — Alluvial cones and fans are also deposited in moist regions where a main stream is unable to remove the rock and silt carried into it by its tributaries. In such cases, the cone or fan forces the main stream over to the opposite side of the valley, compelling it to undercut its bank. This may cause the formation of rapids, with a shallow lake above. The Lütschine River, in the Lauterbrunnen valley in Switzerland, has built an alluvial fan which has divided the lake into which the river flows into two parts, Lake Brienz and Lake Thun (Fig. 117). Fans in humid regions may be of considerable extent, and are well-developed in portions of the Rhone valley in Switzerland and in the larger valleys of the French Alps. Since they are well-drained and usually fertile, they are often the sites of villages.

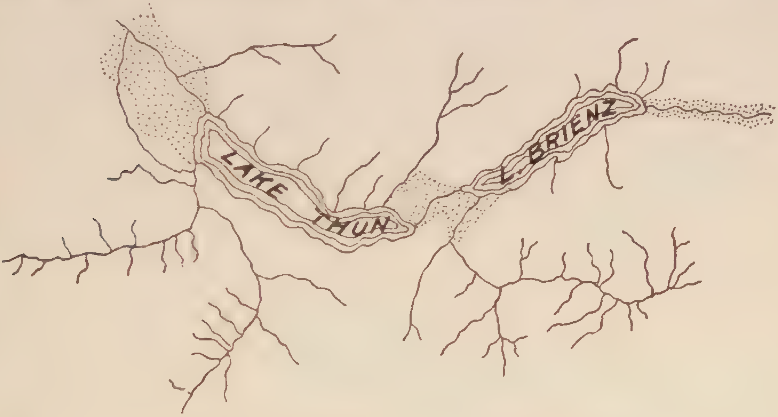


FIG. 117. — Lake Brienz and Lake Thun were formerly one lake, but have been separated by an alluvial fan upon which Interlaken is situated.

Alluvial Terraces. — Terraces are not uncommon in river valleys and are composed either of rock, when they are called *rock terraces* (p. 128), or of stratified clay, sands, and gravels, when they are known as *alluvial terraces*. The latter are fragments of sediments which once filled the valleys to their level, and may be accounted for by meandering and swinging streams, slowly degrading valleys which had previously been aggraded; in other words, by streams slowly eroding their flood plains. Such a change from deposition to erosion may be the result of one or more of several causes. (1) If a region is elevated so as to increase the velocity of the streams, deposition is succeeded by erosion. (2) This is also true if the volume of water in a stream increases without a corresponding increase of sediment. Such a condition may result when a moist climate follows a dry one, or when a stream captures the headwaters of another stream. Alluvial terraces in many dry regions appear to indicate oscillations between dry conditions, when soil and rock waste were washed down from the mountain sides into the valleys, and moist conditions, when the deposits formed in the valley bottoms were dissected because the load of the streams had been diminished. This resulted from the fact that during wet years the soil was held in place by the flourishing vegetation; while during the dry years, although the rainfall was less, the amount of waste removed was great because of the disappearance of the vegetation which formerly bound the weathered rock.

(3) If the quantity of sediment is decreased, as occurs when a stream ceases to erode at its head, deposition gives place to erosion. (4) As a valley lengthens, so much of its load may be dropped in the upper and newer portions of its flood plain that it is enabled to degrade its older flood plain. (5) When a region suffers successive uplifts, so that a stream is unable to cut away its former flood plain before its grade is again increased, terraces will be formed which correspond on the two sides of the valley (Fig. 118). (6) If a degrading stream decreases in volume, it will not be able to occupy the full width of its valley and will cut a narrower valley in the older one. The last-mentioned cause, although perhaps the one which first suggests itself, appears to have been rarely effective in the formation of terraces.

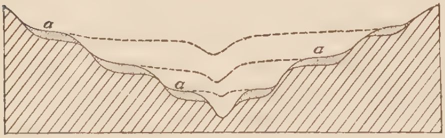


FIG. 118. — Terraces due to uplift. *a*, *a*, *a*, portions of former flood plains.

The close of glacial times (p. 663) seems to have been especially favorable for valley filling, because of the overloading of the streams which derived their material more or less directly from the glaciers as well as from the rapid erosion of new gorges. The depression of the land in many places, as in the Connecticut valley, reduced the velocity of the streams, and occasionally ice jams of long duration also caused deposition. The deposits thus built in valleys have since been partly removed, thus causing the formation of terraces.

Discontinuity of Terraces. — The terraces on the two sides of a valley do not necessarily agree in height. This is due to the fact that, in swinging to and fro across its valley, a stream not only cuts laterally but also at the same time degrades its bed (Fig. 119 *A*, *B*), the flood plain often being higher on one side than on the other. In the Brattleboro, Vermont, region, for example, the stream appears to deepen its valley about 12 feet in each swing. (E. H. Fisher.) If a stream meanders entirely across its valley, it will destroy its flood plain, but if it fails to make a complete swing, a fragment will remain as a terrace. When in its meanderings a stream encounters a rock ledge (Fig. 119) in its valley floor, the lateral cutting may be retarded to such a degree that it will begin to swing to the opposite side of its valley before completing its usual lateral movement. In this way a portion of the flood plain will be preserved as a terrace. When other rock ledges are encountered in its further swings across the valley more terraces will be left, and the "meander belt" will be narrowed. The theory of defending rock ledges affords a better explanation than any other for many of the terraces of the New England valleys.

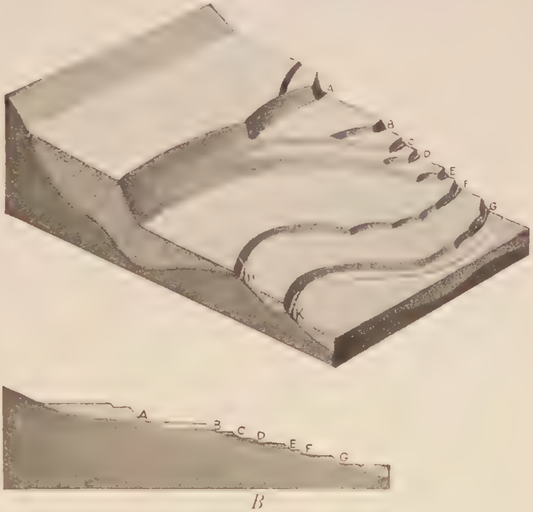


Fig. 119. — Block diagrams showing the origin of stream terraces defended by rock ledges. The terraces *H*, *K*, *A*, *B*, *C*, *D*, *E*, *F*, *G*, owe their preservation to the presence of rock ledges which prevented the stream from cutting them away as the valley was deepened. The relation of rock to alluvium on the right of the block diagram is also shown in figure *B*. (Modified after E. H. Fisher.)

Characteristics of River Deposits. — A cross section through a river deposit does not show a homogeneous deposit of stratified sediment, but rather lens-shaped masses of coarse sands and gravels at different levels, buried in stratified sands and clays (Fig. 107). When traced up or down the valley, these deposits are found to lie in long and comparatively narrow belts. They represent the former channels of the aggrading river, where the current was strong enough to remove all but the coarser material of its load. The finer deposits — the mud and fine sand — were laid down in the more sluggish water on either side of the channel and on the flood plain. Beds of muck, marking the sites of shallow lakes and swamps, are also common.

DELTAS

Deltas are formed where streams enter either lakes or seas. If the body of water into which the river flows is large, all of the sediment carried in by the stream is dropped, and the bottom is gradually built up at the river's mouth. Since sediment settles much more quickly in salt than in fresh water, it is dropped more quickly in the ocean. Because of the low gradient, a river often splits into several channels (Fig. 120) as it enters its delta, the branches being known as *distributaries*.

The shape of a delta, as the name implies, is usually that of the Greek letter of that name, with one angle of the triangle pointing upstream.

Fig. 120. — The delta of the Mississippi River.

Growth of Deltas. — The rate of growth of a delta depends upon (1) the amount of sediment carried by the river, (2) the depth of the sea or lake, (3) the strength of the waves or currents, and (4) the stability of the bottom of the sea or lake where the deposition is taking place. Deltas are apt to be largest in seas in which the tide is weak, since under such conditions practically all of the sediment is dropped soon after it reaches still water. When the ocean bottom at the mouths of rivers is subsiding, the upbuilding of the bottom may be insufficient to compensate for the subsidence. The Mississippi delta has been built upward and outward in spite of subsidence; the sinking which produced the Chesapeake and Delaware bays, however, was so rapid that estuaries were formed (p. 114). The Mississippi River is extending its delta at the remarkable rate of one mile in sixteen years; the Rhone has added a mile to its delta in Lake Geneva since Roman times. It leaves the lake as a clear stream, but gathers sediment from its tributaries in France, with which it builds another delta at its mouth at the rate of about a mile a century. In 220 B.C. the town of Pu-tai, China, stood one third of a mile from the sea, but in 1730 it was 47 miles inland, and to-day it is 48 miles from the shore. (King.) Many of the "points" in lakes are deltas which have been built out by streams.

Structure of Deltas. — A section through a delta shows approximately horizontal beds of fine material at the bottom, which do not differ greatly from other deposits at a similar depth where no delta occurs. These are termed the *bottom-set* beds. Above these are the steeply inclined *fore-set* beds, composed of coarser sediments which have been swept outward by the currents and waves and may have a slope approaching the angle of repose (Figs. 121, 122). The *top-set* beds are nearly horizontal and are laid down upon the fore-set beds. These are usually the last deposits of the river in the upbuilding of the delta.

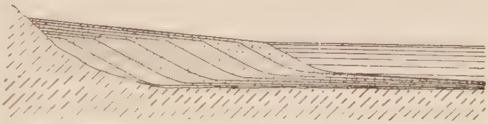


FIG. 121. — Ideal section of a delta built into quiet waters of constant level. The lower horizontal beds are called bottom-set, the inclined, fore-set, and the upper, top-set. (After Barrell.)

The surface of a delta is comparatively level, but gradually rises upstream. In it large and small lakes may occur; the depressions in which they lie being those portions of the delta which, because of the accidental position of the distributaries, were not filled to the general level with sediment. Their life is necessarily short, since they are gradually being filled by accumulations of silt during floods, and by swamp vegetation.

Deltas may be very extensive. That of the Ganges and Brahmaputra has an area of 50,000 to 60,000 square miles, with its head 200 miles from the sea. The length of the Mississippi delta is more than 200 miles, and its area is more than 120,000 square miles. The Orinoco delta has an area larger than that of New Jersey. The head of the delta of the Hoang Ho is 350 miles from the coast. The Imperial valley in California is the result of delta building. The Gulf of California formerly extended 150 miles further northwest than now, and across it a delta was built by the Colorado River, so high as to shut off the upper part of the gulf and inclose a lake of salt water. This lake has almost entirely disappeared and its bed has become the Salton sink. Thanks to irrigation this basin is extremely fertile.

Fig. 122. — Longitudinal section of a delta, showing the dipping, fore-set beds. (Photo. R. S. Tarr.)

The depth of delta deposits is often great. A boring at New Orleans encountered driftwood at 1042 feet, and depths of 500 feet are not uncommon in other deltas. It has been shown that in many cases the subsiding of deltas progresses at a pace about equal to the deposition.

Deltas are usually noted for their fertility. The three most densely populated regions of the world, outside of cities, are the deltas of eastern China, India, and the Po River in Italy. This is true in spite of the fact that, because of their level surfaces, deltas are especially subject to floods. The great flood in the Mississippi River delta in 1912 destroyed many lives and millions of dollars' worth of property, and this was also the case with earlier floods. One of the notable examples of such easily flooded districts is the delta of the Hoang Ho in China. This river is restrained by great dikes (p. 124), some of which are 30 feet above the level of the region; but notwithstanding these precautions many disastrous floods have occurred. For several hundreds of years previous to 1852 this river emptied into the Yellow Sea. In that year, when in unusual flood, it broke through its north levees and emptied into the Gulf of Chihli, some 300 miles farther north. This is only one of the many shiftings which this river has made during its history (Fig. 112). During a flood in 1887 many villages were destroyed, and the loss of life through drowning and famine exceeded 1,200,000 people, more than the entire population of Nebraska.

Deposition in Lakes by Streams and by Other Agents

Mechanical Deposits. — Streams deposit their loads when they flow into lakes, forming deltas (p. 130) at their mouths and covering the bottom of the lake with the finer silt, which is carried farther out since it remains in suspension longer. Lakes may in time be entirely filled by the growth of their deltas, first becoming swamps and then level meadows through which the streams may flow in meandering courses (Fig. 123 *A*, *B*). Meadows of this history are abundant in regions which have been glaciated, such as Michigan, New York, and Minnesota. Lakes are shallowed by the waves cutting back the cliffs along their shores and carrying out into them the material thus derived.

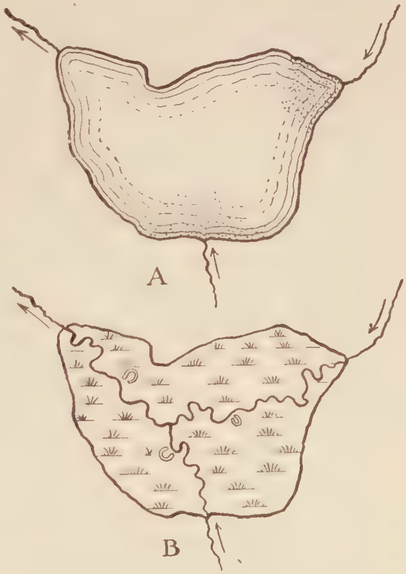


Fig. 123. — Map *A* shows a lake being filled in with sediment carried by streams. Map *B* shows the same lake converted into a marsh, with the streams flowing in meandering courses.

It is thus seen that as soon as a lake comes into existence, agencies arise which tend to obliterate it; sediment begins to fill it, and the outgoing stream commences to deepen the outlet and thus in time to drain it.

Lakes equalize the flow of streams, preventing floods, and also act as filters.

Chemical Deposits. — In addition to such mechanical deposits as those described, chemical deposits are also found in lakes. Lime is sometimes deposited, and iron in the form of limonite (p. 686) is precipitated. In some of the lakes of Sweden and Canada iron of this origin is so abundant as to be of economic importance.

Organic Deposits. (*a*) *Diatoms.* — Dredgings in lakes show that the bottoms are sometimes covered with thick deposits of diatoms (microscopic plants which secrete siliceous tests, p. 581). Since these organisms multiply with great rapidity, they may form extensive deposits, called *diatomaceous* earth.

(*b*) *Marl.* — Calcareous deposits in the form of *marl* may accumulate to great depths in lakes. This is a white, or gray, clay-like deposit which is composed largely of calcium carbonate. It is formed either by the accumulation of shells, or through the agency of certain plants (algæ) which extract carbon dioxide from the water and thus cause the deposition of the lime dissolved in the water. Marl is formed only where small quantities of clay are washed into the lake, since, if large quantities are carried in, the deposit would be termed mud. Deposits of marl may be a score or more feet in depth and are often overlain by peat. In regions where limestone is not accessible, marl is sometimes used in the manufacture of Portland cement.

(*c*) *Peat.* — A brown deposit, called *peat*, composed of the partially decayed remains of plants, sometimes accumulates in swamps, marshes, and shallow lakes. Peat forms most rapidly in cool, moist climates where, although the vegetation may not grow rapidly, the low temperature retards decay. Under favorable conditions it also accumulates in warm countries. In Florida, for example, there are considerable areas of peat. Extensive areas of peat occur in the United States, such as that of the Dismal Swamp of Virginia and North Carolina. In Massachusetts, it is estimated that there are 15,000,000 cubic feet of peat. One tenth of the surface of Ireland is underlain by peat, and large areas in Europe and elsewhere are provided with it. Peat is dried and used for fuel in some regions where it occurs in great abundance, and where its extraction is easy.

Playas. — In desert regions, where no permanent lakes occur, streams sometimes reach depressions when their volumes are increased during the wet season or by cloud-bursts, and form temporary, shallow lakes which may cover large areas. The largest in Nevada is in the Black Rock desert and is 450 to 500 square miles in area, although seldom more than a few inches deep. Such temporary desert lakes are called *playas*. Their beds, when dry, are covered with fine clay and sand, and sometimes with gypsum and salt. On the mud of ancient playa beds the footprints of extinct animals have been preserved (p. 379).

Salt Lakes. — A salt lake may be formed (1) by the cutting off of an arm of the sea by a delta, as in the case of the Salton Sea, California (p. 132), or by an elevation of the sea bottom, which isolates a body of water. Under such conditions, the water will, at first, have the same composition as sea water. If, however, the water flowing into the lake exceeds the evaporation of its surface, it will gradually be freshened. Such was the history of Lake Champlain. If, on the other hand, such a lake has been formed in a desert region where evaporation is excessive, the water will become more salty as time goes on. The Caspian Sea was formerly connected with the Black Sea, but is now isolated and is growing more salty.

(2) Salt lakes are also formed by the concentration of fresh water. Basins in arid regions which do not receive enough water to cause them to overflow may, in time, become saturated with salts of various kinds. The streams bring in common salt ($NaCl$), gypsum ($CaSO_4 \cdot 2\,H_2O$), Epsom salt ($MgSO_4 \cdot 7H_2O$), and calcium carbonate ($CaCO_3$), which they obtain from the rocks over which they flow. These salts may accumulate in the lake as evaporation proceeds, until the water becomes so concentrated that they are precipitated. Iron oxide and calcium carbonate will be deposited first; upon further concentration, gypsum, which is insoluble in strong brine, will be precipitated; then common salt and Glauber salts (Na_2SO_4), in the order of their solubility. This order is often interfered with under certain conditions. Cold weather, for example, will cause the precipitation of Glauber salts (Na_2SO_4) before the common salt has all been precipitated. If the evaporation of the surface of the salt lake does not equal the amount of water received during a wet season, the deposition of gypsum and salt will cease, and the beds of salt may be covered by the sediment brought in by the streams. With the recurrence of the dry season the deposit of gypsum and salt will commence again. Many alternations of mud and salt are encountered in wells sunk on the margins of salt lakes. In some salt lakes most of the salt has been deposited, and the liquid remaining, called

"bittern," contains chiefly Epsom and Glauber salts. The Dead Sea is such a lake.

(3) The salt of some salt lakes has been attributed to an accumulation of wind-blown salt. Perhaps the best example of a salt lake in which this origin is evident is furnished by a lake in northern India (Sambhar Lake). This lake is situated in an inclosed basin more than 400 miles inland and appears to receive the greater part, if not all, of its salt from dust-laden winds which sweep over the plains between it and an arm of the sea during the dry months. Analysis of the air during the dry season shows that at least 3000 metric tons of salt are carried over the lake annually, an amount sufficient to account for the accumulations of salt in the lake.

Alkaline Lakes. — Alkaline and borax lakes differ from salt lakes in that they contain a predominance of sodium carbonate or borax. The source of this carbonate and borax, as in the case of common salt, is the rocks over which the streams which feed such lakes flow.

Origin of Rock Salt. — Deposits of salt underlie many hundreds of square miles of sedimentary rocks in New York and other states. The thickness of the salt beds varies greatly, the thickest reported in New York consisting of 325 feet of solid salt. The greatest salt deposit known is that at Stassfurt, Germany, which is 4794 feet deep. Since salt and gypsum occur together, it is believed that such deposits have been formed as a result of the evaporation of salt lakes. One objection to this theory is the great thickness of some beds and their purity. In the case of such deposits it is believed that an estuary or lagoon was separated from the sea by a bar over which water was carried during storms or perhaps at high tide. If the region in which this occurred was hot and arid, it is conceivable that salt might be deposited to the depth of the lagoon or estuary. If such a basin should slowly subside, a bed of salt of great thickness could result. Such remarkably thick deposits as those in Louisiana, where the bottom has not been reached at a depth of 2000 feet, requires a still further modification of the theory.

Extinct Lakes. — Upon their disappearance lakes leave behind them proofs of their former existence. If they were of comparatively short duration, as would be the case if they had been formed by ice jams (p. 186), their former presence might be attested by (1) the deltas deposited by the streams which flowed into them, as well as by (2) the stratified sand and clay which were spread over their beds. When their life was long, (3) wave-cut terraces, (4) sand bars and

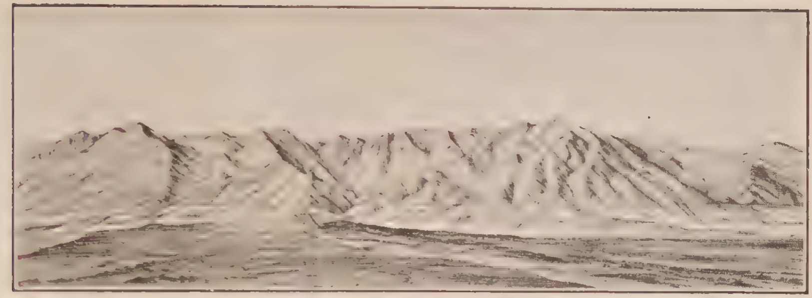


Fig. 124. — Deltas formed in Lake Bonneville by the Logan River, Utah. (U. S. Geol. Surv.)

spits, deltas, and other thick deposits are left (Fig. 124). One of the most remarkable lakes of this sort was Lake Bonneville (Fig. 125), of which the Great Salt Lake is a withered remnant. This lake at

Fig. 125. — Contour map of the shore terraces of Lake Bonneville, Utah. The terraces were cut and built at different lake levels. (U. S. Geol. Surv.)

its greatest extent covered 19,750 square miles and was 1000 feet deep. At this time it had an outlet to the north which carried the excess waters to the Pacific. During this period, too, great terraces were cut and immense deltas were built. From Salt Lake City one can see these terraces on the lower slopes of the mountains and from them can learn the former levels of the lake. A change in climate finally reduced this extensive lake to the present relatively small Great Salt Lake, which has an area of 2000 square miles and an average depth of 15 feet. Since the water now contains 18 per cent. of salt, it is so dense that the bather is required to exert no effort to keep his head above water, as it is impossible to sink.

REFERENCES FOR THE WORK OF STREAMS

General

Cleland, H. F., — *North American Natural Bridges, with a Discussion of their Origins:* Bull. Geol. Soc. America, Vol. 21, 1910, pp. 313–338.

De Martonne, E., — *Géographie Physique*, pp. 413–442.

Gilbert, G. K., — *Report on the Geology of the Henry Mountains:* U. S. Geog. and Geol. Surv. of the Rocky Mountain Region, 1877, pp. 99–150.

Haug, E., — *Traité de Géologie*, pp. 406–436.

Russell, I. C., — *Rivers of North America.*

Salisbury, R. D., — *Physiography* (*Advanced*), pp. 114–203.

Salisbury and Atwood, — *The Interpretation of Topographic Maps:* Professional Paper, U. S. Geol. Surv. No. 60, 1908.

Shaler, N. S., — *Aspects of the Earth*, pp. 143–196.

Taylor, F. B., — *Niagara Falls Folio:* U. S. Geol. Surv. No. 190, 1913.

Flood Plains

Davis, W. M., — *The Development of River Meanders:* Geol. Mag., Vol. 10, 1903, pp. 145–148.

Jefferson, M. S. W., — *Limiting Widths of Meander Belts:* Nat. Geog. Mag., Vol. 13, 1902, pp. 373–384.

Cycle of Erosion

Davis, W. M., — *Geographical Cycle*, Geographical Essays, 1909.

Davis, W. M., — *Base Level, Grade, and Peneplain:* Jour. Geol., Vol. 10, 1902, pp. 77–109.

Davis, W. M., — *The Peneplain:* Am. Geologist, Vol. 23, 1899, pp. 207–239.

Stream Piracy

Bowman, I., — *A Typical Case of Stream Capture in Michigan:* Jour. Geol., Vol. 12, 1904, pp. 326–334.

Darton, N. H., — *Examples of Stream Robbing in the Catskill Mountains:* Bull. Geol. Soc. America, Vol. 7, 1896, pp. 505–507.

Davis, W. M., — *Stream Contest along the Blue Ridge:* Bull. Geog. Soc. Philadelphia, Vol. 3, 1905, pp. 213–244.

TERRACES

DAVIS, W. M., — *The Terraces of the Westfield River, Massachusetts:* Am. Jour. Sci., Vol. 14, 1902, pp. 77–94.

DAVIS, W. M., — *River Terraces in New England:* Bull. Harvard Collection, Museum of Comparative Zoölogy, Vol. 38, 1902, pp. 281–346.

DODGE, R. E., — *The Geographical Development of Alluvial River Terraces:* Proceedings Boston Soc. Nat. Hist., Vol. 26, 1894, pp. 257–273.

FISHER, E. F., — *Terraces of the West River, Brattleboro, Vermont:* Proceedings Boston Soc. Nat. Hist., Vol. 33, 1906, pp. 9–42.

INTRENCHED MEANDERS

DAVIS, W. M., — *The Seine, the Meuse, and the Moselle:* Nat. Geog. Mag., Vol. 7, 1896, pp. 189–202; 228–238.

DEPOSITION

BARRELL, J., — *The Geological Importance of Continental, Littoral, and Marine Sedimentation:* Jour. Geol., Vol. 14, 1906, pp. 316–356; 430–457; 524–568.

SALT LAKES

HARRIS, G. D., — *Rock Salt, Its Origin and Importance:* Bull. La. Geol. Surv. No. 7, 1907.

TOPOGRAPHIC MAP SHEETS, U. S. GEOLOGICAL SURVEY, ILLUSTRATING THE WORK OF RUNNING WATER

Regions in Topographic Youth

Casselton, North Dakota.
Fargo, North Dakota.
Bright Angel, Arizona.
Kaibab, Arizona.
Bisuka, Idaho.
Milan, Illinois.
Niagara Falls, New York.
Great Falls, Montana.

Regions in Topographic Maturity

Charleston, West Virginia.
Briceville, Tennessee.
Lancaster, Wisconsin–Iowa–Illinois.
Becket, Massachusetts.
Arnoldsburg, West Virginia.
Monterey, Virginia–West Virginia.

Regions in Topographic Old Age

Caldwell, Kansas.
Butler, Missouri.
Morrilton, Arkansas.

Stream Piracy

Kaaterskill, New York.
Lake, Yellowstone National Park, Wyoming.
Gloversville, New York.
Lykens, Pennsylvania.

Rejuvenated Streams and Entrenched Meanders

Lockport, Kentucky.
Harrisburg, Pennsylvania.
Huntingdon, Pennsylvania.
Ravenswood, West Virginia–Ohio.

Topographic Map Sheets, Illustrating Stream Deposits

Alluvial Fans

Cucamonga, California.
Sierraville, California.
Desert Well, Arizona.
Parker, California–Arizona.

Braided Streams

North Platte, Nebraska.
Kearney, Nebraska.
David City, Nebraska.
Gothenburg, Nebraska.
Disaster, Nevada.

Natural Levees

Donaldsonville, Louisiana.
Baton Rouge, Louisiana.
Hahnville, Louisiana.

Flood Plains and Meanders

St. Louis, Missouri.
Butler, Missouri.
Lake Providence, Louisiana.
Jefferson City, Missouri.

Terraces

Cohoes, New York.
Lacon, Illinois.
Hartford, Connecticut.
Mountain Home, Idaho.

first Chap 18
also
643-649

CHAPTER V

THE WORK OF GLACIERS

WHEN viewed from an eminence, a mountain glacier has the appearance of a river of ice flowing down a valley to a point where it ends abruptly and a stream emerges from beneath it and courses toward the sea. If the climate is cold, as in Greenland, glaciers may even reach the sea, where their shattered fronts are carried away as icebergs by the ocean currents.

GENERAL CONSIDERATIONS

Distribution and Size of Glaciers. — Glaciers exist on high mountains, even in the tropics. In temperate regions they abound on high ranges, especially on those against which moisture-laden winds blow; as, for example, the Sierra Nevada, the Cascade ranges, the Alps, the Caucasus, the Andes, and the Himalayas.

Mountain glaciers vary in size from those which barely extend beyond their cirques (hanging, cliff, or corrie glaciers) to the great Seward Glacier of Alaska, more than 50 miles long and 3 miles wide where narrowest. In the Alps there are 2000 glaciers, the largest of which, the Aletsch Glacier (p. 187), is more than 10 miles long, although the majority are less than a mile. These Alpine glaciers vary in width from a few hundred feet to about one mile. "The thickness of ice in the Alpine glaciers must often be as much as 800 to 1200 feet," the depth usually being least at the lower end. Great glaciers are confined to polar regions (continental glaciers, p. 168) and to high mountains of the temperate zones.

Position of the Snow Line. — The level on the earth's surface above which some of the snow of one winter lasts through the following summer, thus forming areas of "perpetual snow" or snow fields, is called the *snow line*. Its position depends upon the normal temperature of the region as well as upon other factors. In general, the snow line varies little from the line on which the average temperature is 32° F. Near the equator it is 15,000 to 19,000 feet above the sea, while in polar regions it is almost, or quite, at sea level. In intermediate regions the height increases toward the equator. In the Alps the snow line is 8500 feet above the sea; in the western United States and in British Columbia the higher mountains are covered with perpetual snow; in Massachusetts it has been shown by kites that glaciers would exist at an altitude of 11,470 feet; and it is estimated that glaciers would develop in the Scottish Highlands if the average temperature were lowered three degrees.

The position of the sun with reference to a mountain range influences the height of the snow line. In the northern hemisphere, for example, other things being equal, the snow line will be lower on the north side of a mountain than on the south side, since the former receives heat from the sun fewer hours each day. Certain forms of topography also favor the retention of snow. For instance, snow gathers to greater depths in deep ravines than on a level surface, as it is blown in by the wind and protected from the sun's heat so that it may remain from one winter to the next. A moist climate also favors a low snow line on account of the greater snowfall, since more time is required to melt, or evaporate, a thick layer of snow than a thin one. On the Himalayas the snow line is 3000 to 4000 feet lower on the south than on the shaded north side, because of the greater amount of snow precipitated there by the moist, south winds from the Indian Ocean. The few inches of snow which fall on the north slope may be melted in a few warm summer days, while the several feet of snow on the south side may not disappear, even when subjected to a longer period of warmth. In dry climates the snow may disappear entirely by direct evaporation. As far as temperature is concerned portions of Siberia are under glacial conditions, but the climate is so arid and the snowfall so scanty that the snow which falls is soon evaporated.

Formation of Ice in Snow Fields. — Snow differs from ice in being composed of fine crystals, loosely consolidated and separated from one another by air, whereas ice consists of crystals in contact. In a snow field there is every gradation from fluffy snow to granular snow or *névé* and finally to solid ice. The change from one state to the other is well shown in snowdrifts of the temperate zone, which become granular if they exist for a few months, the granules being about the size of small hailstones. If they exist still longer, the drifts are represented by small mounds or ridges of solid ice. The transformation from snow to névé and then to ice is very gradual and is accomplished (1) by the pressure of the overlying snow which forces the air from between the snow crystals and thus tends to compact them;

(2) by rain and the water from the upper layers of the melting snow, which soaks down into the snow, freezes, and expels the air; and (3) by the growth of the snow crystals. It is in this way that the coarsely granular snow seen in drifts in the early spring and in the névé of snow fields is produced. The growth of the crystals is accomplished partly at the expense of the smaller crystals which lose bulk by evaporation, while their larger neighbors take the moisture given off to increase their own size, and partly from the thaw water which bathes them. Névé passes insensibly into snow, on the one hand, and into ice on the other. A crystallographic study shows that ice is made up of crystals, the external form of which has been obliterated by pressure and as a result of their growth. Ice is, therefore, a crystalline rock, like marble, and is classed as a rock.

Snow does not accumulate indefinitely above the snow line; a part melts and runs off, a part is evaporated, and a part is carried away by glaciers. It has been estimated that if glaciers had ceased to drain the snow fields at the beginning of the Christian era, the Alps would now be buried under a mantle of snow about 5000 feet thick.

Mountain Glaciers

Formation. — When ice has accumulated to a considerable depth it tends to spread, much (so far as external appearance is concerned) as does a mass of stiff molasses candy; and if it rests on an inclined surface, it tends to move down the slope. When the ice in an ice field begins to move it is called a glacier.

If we study typical glaciers, such as those in the Alps, in Glacier National Park, in British Columbia, or in Alaska, we find that in general they are similar but show individual differences. We find, upon following a glacier to its head, that it begins in a broad amphitheater (Fig. 126), called a *cirque* (French for amphitheater), above the snow-covered floor of which rocky walls rise precipitously, often to a height of several hundred feet. In this amphitheater snow gathers to great depths, often to hundreds of feet. The snow comes from the frequent storms which rage there and from the accumulations on the walls of the cirque, from which it is swept in by winds or carried by avalanches. Cirques are therefore the feeding grounds of mountain glaciers. In them one finds every gradation, from snow which is freshly fallen, through granular névé or half-formed ice, to compact ice. From the cirque the solid ice of the glacier moves slowly down the mountain valley until it reaches a point where the melting equals the forward movement (p. 159), the size of the glacier depending (1) upon the area of the névé field drained by it, (2) upon the amount of the precipitation, and (3) upon the rate of melting. Sometimes glaciers flow between forests and even cultivated fields, as, for example, in the valleys of Grindelwald and Chamonix, where glaciers lie within a few hundred feet of the homes of the inhabitants. In New Zealand a glacier from the Mt. Cook range discharges its débris in the midst of subtropical vegetation.

FIG. 126. — Cirques or feeding ground, and medial moraine of the Breithorn Glacier. (Photo. L. E. Westgate.)

Cirques. — One of the most striking and beautiful features of the Alps in Switzerland, of the Selkirks in Canada, of the Rocky Mountains of the United States, and of other high mountains of the temperate regions are the ragged crests (Fig. 127) separating the gigantic semicircular *cirques*, which hang high up on the mountain sides. These cirques dominate the high mountains and correspond to the limit of perpetual snow of the Glacial Period (p. 141). Their walls are rough and precipitous, while their floors are comparatively smooth and

FIG. 127. — Cirques and small glacier, St. Christophe, France.

level, the former having been roughened by the attacks of the frost and other weathering agents and the latter having been scoured by glaciers into rounded surfaces. Most of the lakes of the high mountains, which give such scenery much of its charm, rest in cirques. They lie in basins, formed either by dams of glacial débris (moraines) left by glaciers, or in depressions cut into the solid rock of the cirque by the ice (rock basins). An understanding of the origin of cirques is, therefore, necessary for an appreciation of the scenery of high mountains.

Origin of Cirques. — If the average temperature of a mountain region is being lowered as a result of a change in climate, the drifts of snow which accumulate in ravines and spots sheltered from the full heat of the sun may last from one season to the next. On account of the weight of the snow and for other causes (p. 142), the lower layer will be compressed into ice and will slowly move down the slope. This movement will separate the moving mass of snow and ice from the snow which rests upon the upper slope, near the valley wall. The rock wall will thus be partially exposed, and a crevasse, called the *Bergschrund* (German for mountain gap or fissure), will be formed (Fig. 128). The Bergschrund, in fact, marks the line where the real downward motion of the névé begins. Crevasses of this sort vary in width from two or three feet to more than 80 feet, and play an important part in the formation and enlargement of cirques. One such Bergschrund, 150 feet deep, which extended down to the rock bottom of the cirque, was explored, and its floor was found to be composed of rock masses, partly or completely dislodged from the wall of the cirque. During the days of summer the water from the melting snow drips down into the crevasse, wetting the rocks and filling the cracks. As soon as the sun sets the temperature of such regions is rapidly lowered and the water filling the cracks and joints freezes, forcing the blocks from the sides. Since the cracks at the base of the rock wall are more completely filled with water than are those in the upper portion, the greatest disruptive effect is at the bottom of the crevasse, thus tending to produce and maintain vertical walls. As the cirque is enlarged by the wedge work of the ice on the rock in the Bergschrund, the crevasse also moves back. The circular form of the cirque results from the movement of the snow and ice away from the surrounding walls toward the center of the depression.

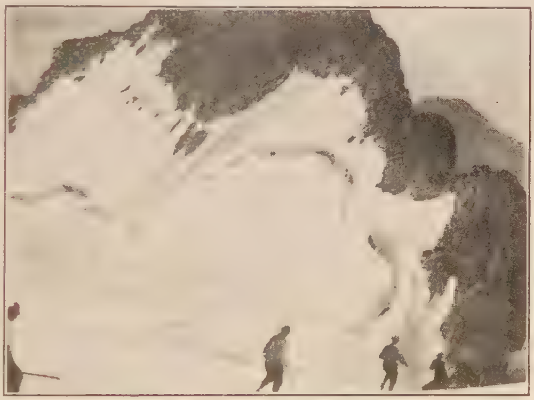


FIG. 128. — The Bergschrund of a glacier. Swiss Peak, British Columbia. (Photo. L. E. Westgate.)

The development of cirques is apparently not necessarily limited to the heads of former stream valleys, although this is generally the case, but they may have their origin in a somewhat different way. If the drifts on a mountain slope last year after year until late in the spring, it will be found that their edges are usually bordered by fine soil which is slowly being removed by water and deposited in deltas at the lower margins of the drifts. This fine soil is the result of the alternate freezings and thawings of the water in the cracks and pores of the rock, which is thus finally broken up into small fragments. In this way, by *nivation*, a niche, the beginning of a cirque, may be formed on a mountain slope.

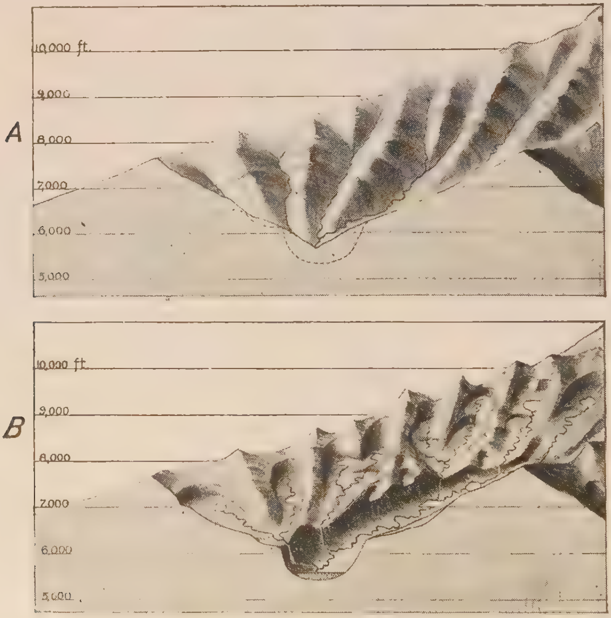


FIG. 129. — *A* shows mountain valleys formed by stream erosion. *B* shows the same valleys after they had been occupied and strongly eroded by glaciers. The main valley has become U-shaped, and the side valleys have become hanging valleys with strongly developed cirques. An attempt has been made to show the probable approximate deepening, in feet, by glacial erosion. (After W. C. Alden.)

Development of Cirques. — A high region which has been partly cut into cirques "resembles nothing so much as a layer of dough from which biscuit have been cut." As the amphitheaters or cirques on the two sides of a mountain ridge enlarge, they finally encroach on each other, first forming a narrow, ragged, comb-like ridge (Fig. 129 *B*), and somewhat later, as the separating walls of the cirques are partially quarried away, producing tooth-like peaks.

Fate of Cirques. — If changes in climate cause a glacier gradually to melt back into its cirque and finally to disappear, the characteristic features of the abandoned cirque are slowly obliterated; landslides and talus descending from the cliffs are heaped upon the bottom, filling the lakes and covering the bottom; the morainic (p. 159) or rock ridge at its entrance is breached by a gorge cut by the outflowing stream; side valleys are developed; and the resulting topography presents few features to indicate that it was developed from a cirque.

Ablation. — The surfaces of glaciers are constantly being lowered by direct evaporation and by melting; those of the Alpine glaciers are lowered from 18 to 25 feet during the summer months, that of the Mer de Glace having been lowered twenty-four and a half feet in 1842. Since the advance of a glacier depends upon the thickness of its mass, it follows that when ablation is excessive the front will retreat. A retreating glacier is, consequently, thinner and, unless its valley walls are vertical, narrower than when it was advancing.

Surface of Mountain Glaciers

The surface of a glacier is usually rough (Fig. 130) as a result of a number of causes.

(1) **Irregularities Due to Tension.** — Because of the brittleness of the ice mass, glaciers are broken by cracks called *crevasses*. Some of these are the result of the more rapid motion of the center than the retarded sides, which produces strains under which the ice fractures. The crevasses formed in this way are diagonal and extend up the valley (Fig. 136 *C*, p. 151). Where a glacier emerges from a narrow portion of its valley longitudinal cracks are developed, and the tension on a curve produces transverse crevasses which

Fig. 130. — Surface of a glacier showing seracs and crevasses.

rise obliquely from the bottom, since the latter portion of the ice is retarded by friction with the bed. Crevasses when first formed are usually separated from one another by relatively level surfaces, but since their upper portions are soon widened by melting, the intervening ice often becomes blade-like in its sharpness, so that the surface of the glacier presents a maze of sharp ridges. Such a ridge of ice is called a *serac* (Fig. 131). In crossing a glacier, such as the Mer de Glace, the chief difficulties encountered are these sharp, steep ridges of ice.

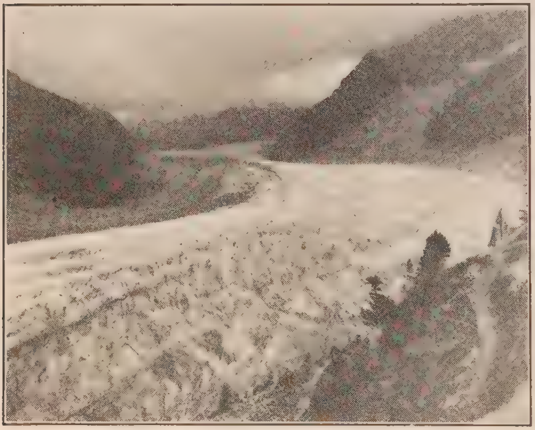


Fig. 131. — The Aletsch Glacier, Switzerland.

The most conspicuous roughness of a glacier's surface develops where there is a sudden change in the slope of the bed (Figs. 132, 133). In a river this would produce a waterfall, and in a glacier it produces an *icefall*. Such icefalls make travel on a glacier extremely difficult and dangerous. The ice passes over the fall slice by slice, the fall (as in a river) remaining stationary. Below the fall the blocks heal together, but the resulting surface is extremely rough, although it gradually becomes smoother.

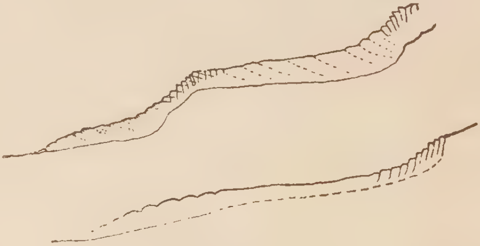


Fig. 132. — Longitudinal sections of a glacier showing icefalls formed where the slope of the bed of a glacier increases suddenly. (After Heim.)

It is not to be understood that a glacier is much fractured in all parts. The absence of cracks on portions of the Aar Glacier is shown by the fact that a pond 20 feet deep and covering 10 acres existed for 24 years and was carried a distance of 600 feet.

(2) **Irregularities Due to Streams and Ice Tables.** The surfaces

of glaciers become irregular in other ways besides fracturing. Water from the melting ice forms rivulets, which erode and melt channels in the ice. When such a stream reaches a crevasse it plunges down, forming a circular shaft called a *moulin* (French for mill). As the ice moves on, this opening is closed and a new one formed in its place. Thus a series of inactive moulins, in various stages of preservation, are left extending down the glacier from the active one. The active moulin, however, may be said to remain stationary or confined to narrow limits, and may, in time, excavate potholes (p. 93) many feet in depth in the rock beneath the glacier (Fig. 134).

Fig. 133. — Denver Glacier, Alaska, showing an ice-fall, feeding grounds, and lateral and medial moraines. (Photo. F. B. Sayre.)

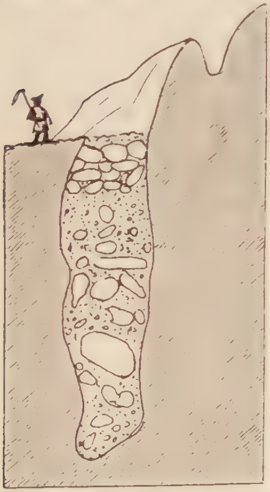


Fig. 134. — A giant pothole formed in the bed of a glacier by the water, sand, and gravel carried through a crevasse. Near Christiania. (After A. Geikie.)

Since the ice of a glacier varies in compactness it melts unevenly, and this also tends to produce a rough surface.

The surface of a glacier is also roughened by the irregular melting of the ice, due to the accumulation of débris. If a fragment of rock which has fallen on the ice is too thick to be heated through by the sun it will protect the ice beneath from melting. Because of this it may in time stand on an ice pillar several feet in height, forming an *ice table* (Fig. 135). After a time the pillar may become so high that the sun will be able to melt it. The protecting cap of rock will then be undermined and will slide off, on the south side in the northern hemisphere, and will then be ready to cause the formation of another column.

The portions of a glacier over which dust or thin layers of earth are spread will be melted more rapidly than those not so covered, since the dark dust absorbs heat more rapidly than does ice. In this way *dust wells* and other irregular hollows several inches in depth are formed, the depth depending upon the diameter of the hollow and the angle at which the sun's rays strike it. The great drifts of snow which had to be removed each spring during the construction of a railroad in Norway were scattered over with fine dust in order that they might be more quickly melted by the sun. If, however, dust is more than an inch thick it prevents the underlying ice from melting and forms *dirt cones*.

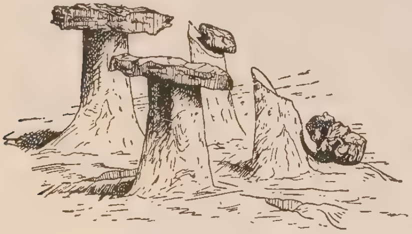


Fig. 135. — Ice pillars protected by slabs of rock. Parker Creek Glacier, California. (After Russell.)

Often the greatest irregularities on mountain glaciers are the long lines of rock débris (surface moraines) which may be of considerable thickness and which usually rest upon high ice ridges formed by the protecting cover of the former.

The water from the moulins and that which reaches the bottom of the glacier in other ways, as for example that melted from the lower surface of the glacier by friction, that which comes from the springs in the valley through which the glacier is moving, and that which seeps through the cracks of the ice, all emerges from a tunnel in the end of the glacier as a single stream, often of considerable size. These streams flow even throughout the extreme winters of glaciated regions.

MOVEMENT OF GLACIERS

The Swiss early had reason to believe that glaciers move, as was shown when two glaciers advanced over fields and meadows, upsetting barns and filling the quarries from which the citizens of Bern obtained their marble. A recent example of this sort occurred in 1909 1910, when the advancing Child Glacier in Alaska threatened to destroy a $1,400,000 steel bridge.

Rate of Movement. — It was not, however, until 1827 that any serious attempts were made to determine the rate at which glaciers move. In that year Hugi built a hut upon the Aar Glacier in Switzerland and noted its position from year to year. In fifteen years it had moved 1428 meters, or about 100 meters a year. Forty-four years later the remains of the hut were found 2408 meters lower down the valley. Since these first measurements careful surveys have been made from time to time, and it has been found that the motion of Alpine glaciers seldom exceeds one third to two thirds meter (one to two feet) a day. In 1861 the heads of three guides with some hands and fragments of clothing appeared at the foot of the Bossons Glacier on whose névé they had been buried beneath an avalanche forty-one years before. So perfect was the preservation that they were easily recognized by a guide who had known them in life. The rate of movement had been eight inches a day.

In large glaciers, however, the rate is much more rapid. It is estimated that the Child Glacier in Alaska moves about 30 feet a day during the summer, and a large glacier which drains the snow fields of north Greenland is said to have moved more than 60 feet in a single day. These latter figures are exceptional and apply only to very large and thick glaciers. Large glaciers, however, do not always move faster than small ones, since other conditions may counterbalance the greater thickness.

Differential Movement of Glaciers. — By placing stakes in a straight line across the surface of a glacier and a vertical row on a side exposure, it was found that the middle of a glacier moves faster than the sides (Fig. 136 *A*) and the top faster than the bottom (136 *A*, *B*). In one glacier, while the top moved 6 inches, the middle moved only 4.5 inches, and the bottom 2.5 inches. The reason for the slower motion of the sides and bottom is evidently to be found in the friction with

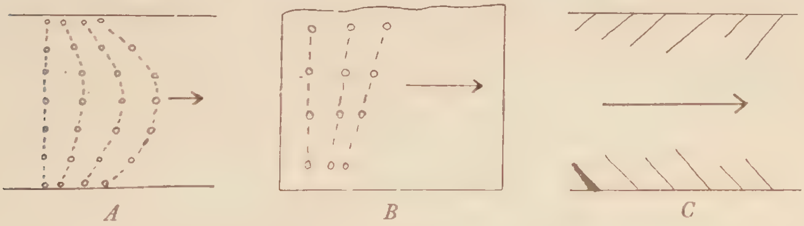


FIG. 136. — Diagrams showing the movement of glaciers. *A*, a line of stakes placed in a straight row across a glacier becomes more and more curved each day. *B*, a line of stakes placed in a vertical row on the exposed side of a glacier becomes more and more inclined. *C* shows the formation of marginal fissures produced by the pulling of the more rapid central portions upon the slower marginal portions.

the walls and bed of the valley through which the glacier flows. It follows from the above that the rate of movement will be reduced if the bed of the glacier is rough, and that a smooth bed will favor rapid motion.

It has been found that the line of swiftest motion is not always in the middle of glaciers, but that as in the case of rivers, although to a lesser degree, it is deflected from side to side, being nearer the outside of a curve.

Factors Influencing the Rate of Movement. — The rate of movement of a glacier increases with (1) the slope of the bed upon which it rests, but depends even more upon (2) the slope of the upper surface of the ice and upon (3) its thickness. A general inclination of the upper surface of a glacier is necessary for glacial movement, although for short stretches the surface of the ice may even have a backward slope. The beds of valley glaciers slope in the general direction of the movement of the ice, but there are many local exceptions, as is shown by the deep basins in valleys formerly occupied by glaciers. The great ice sheets of North America moved to the south over a land surface which for many miles sloped towards the north, *i.e.*, in the direction opposite to that of the movement of the ice. In all such cases the upper surface of the ice must have sloped in the direction of the glacial movement.

The velocity of a glacier is greater in summer than in winter, and at midday than at night; that is, when the glacier is melting more rapidly and is most thoroughly saturated with water. The Mer de Glace, France, moves in summer at an average rate of 27 inches a day in the middle and 13 to 19 inches a day near the sides; in winter the rate is about half as much. Other factors influencing the rate of motion of a glacier, besides the slope of the ground, the slope of its upper surface, and the quantity of water with which the ice is saturated, are the amount of load in its basal portions, which tends to retard the rate, and the straightness of its course and the smoothness of its bed, which tend to increase it.

Lower Limit of Glaciers. — Glaciers move down their valleys until they reach a point where the melting (ablation) equals the forward movement (Fig. 137). When the melting exceeds the forward movement, the glacier is said to *retreat;* when it is less the glacier *advances.* It is evident that the lower limit of a glacier will not be fixed (except when it reaches the sea) unless the conditions of temperature and snowfall remain constant. Since both temperature and snowfall usually vary from year to year and, more widely, in cycles,[1] the ends of glaciers are seldom stationary for long periods. If the depth of the snow in the cirque increases during a single year or a number of years, the glacier will advance; while if the snowfall is slight or the average temperature high so that little snow can accumulate, the glacier will retreat. For example, because of the hot summer of 1911 practically all of the glaciers of the Alps were in retreat in 1912, one (the Brenva Glacier on Mt. Blanc) receding 50 meters. The Muir Glacier in Alaska has retreated seven miles in the past twenty years, and the glaciers of the Chamonix valley in the Alps, one quarter to one half of a mile since 1812. In 1858 there was a harbor in Bell Sound, Spitzbergen, at the head of which was a strip of lowland and beyond this a low, but broad glacier. In 1860–1861 the glacier advanced over the lowland, filled up the harbor, and extended far into the sea. It is now one of the largest glaciers in Spitzbergen.

FIG. 137. — The Rhone Glacier, showing crevasses and front.

A large glacier responds to excessive or deficient snowfall more slowly than a small one, and several years may elapse before it shows the effect of such changes.

An unusual cause of rapid glacial advance is recorded from Alaska, where the ice fronts of a number of glaciers have moved forward as a result of earthquake shocks. During an earthquake in 1899 the mountains from which the snow supply of these glaciers is derived were so vigorously shaken that great avalanches of snow and rock were thrown down on the névés. This increased supply caused all of the glaciers in the region affected to advance. They did not all,

---

[1] There appears to be a climatic cycle of 35 years during which a series of cold or rainy years is followed by years which are warmer or drier.

however, show a simultaneous forward movement. The reason for this is to be found in the size of the glaciers. It was discovered that the smaller glaciers advanced more quickly and had, indeed, in 1909 already passed completely through the period of advance, while the long glaciers were at that date (1909) either still advancing or merely beginning to advance.[1]

Transportation by Mountain Glaciers

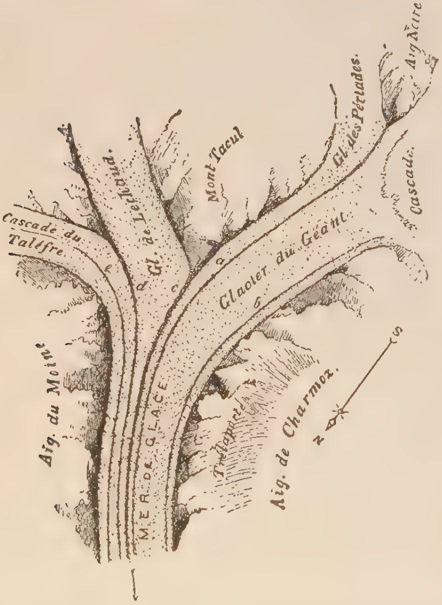


Fig. 138. — Map showing the formation of the Mer de Glace by the union of several glaciers. The development of lateral and medial moraines is illustrated also.

Surface Moraines. — We have seen (p. 29) that in regions where frost is an active agent of the weather, talus, composed of angular rock fragments of various sizes, rests at the bases of cliffs. If the bottom of a valley with high and steep sides is occupied by a glacier, these fragments will fall upon its surface; and as the ice moves on all parts of the glacier's side, will pass under the cliffs which supply the débris. In the process of time, a regular ridge of angular rocks and soil will rest upon the edge of the ice. Such a deposit is called a *lateral moraine* (Figs. 138, 139, 140). The ice of glaciers does not commingle at their confluence, but the masses move on side by side, the two adjacent lateral moraines uniting to form a *medial moraine* (Figs. 138, 139, 140). In this way, by the union of several branches, a glacier may be covered with several medial moraines. A medial moraine may also be formed when a glacier passes over an elevation in its bed from which it scrapes off rock fragments. After the glacier has passed this point the débris

---

[1] *Physiography and Glacial Geology of the Yakutat Bay Region*, Professional Paper No. 64, U. S. Geol. Surv., 1909.

may be exposed by the melting of the surface of the ice and continue to the end of the glacier as a medial moraine. It will readily be seen that the material of the various surface moraines of a glacier may differ widely in composition, since they were derived from the rocks of many parts of the valley. The Baltoro Glacier of Hindu Kush has fifteen moraines of different colors. (Bönnersheim.)

Since the surface moraines are usually sufficiently thick to protect from the sun's rays the ice upon which they rest, they are generally situated on ridges of ice, sometimes 50 to 80 feet in height. After a time the ridges become so high that the morainic material slips off, thus widening the morainic belt. After several repetitions of this process the medial and lateral moraines may cover completely the lower end of a glacier.

Fig. 139. — Diagram and cross section of a mountain glacier. Lateral moraines are seen to produce medial moraines. The movement of the superglacial material to form englacial and finally subglacial material is shown. Icefalls occur near the confluence of the glaciers on the right.

The size of some of the rock fragments carried on the surfaces of glaciers is very great. One such bowlder contained 244,000 cubic feet (Forbes), which is equivalent to a squared stone 122 feet long, 50 feet wide, and 36 feet high. The weight of material which a glacier can carry on its surface is limited only by what it may receive, and the very weight of the surface load will hasten the movement of the glacier. Upon the disappearance of a glacier, these great rock masses are often left in unstable positions and are then known as *balanced bowlders*, or *rocking stones*.

All bowlders transported and deposited by glaciers are given the general name *erratics*. Figure 141 shows a balanced bowlder.

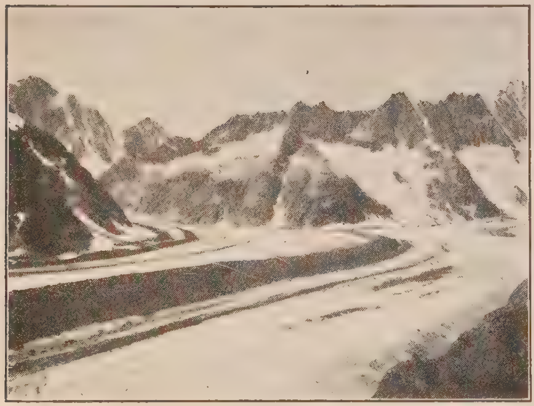


Fig. 140. — Aar Glacier showing lateral and medial moraines, and cirques. (Photo. L. E. Westgate.)

Subglacial Material. — The bottom portions of glaciers contain stones and ground-up rock. This material is derived, either directly from the rock bed or from the superglacial material which reaches the bottom through the crevasses. The subglacial material is usually much worn.

Englacial Material. — Between the surface and the bottom of a glacier some débris may be carried. This is derived in part from the superglacial material which has not reached the bottom through the crevasses, in part from that which gathered on the surface of the snow or névé and was subsequently covered, and in part from that which was scraped off an elevation in the bed. The englacial material may become superglacial by ablation, and subglacial by gradually settling or by the melting of the lower ice. All will be deposited when the end of the glacier is reached.

Fig. 141. — Balanced bowlder, Hoosac Mountain, Massachusetts. The bowlder is so nicely balanced that although of great weight it can be made to vibrate with little effort.

Erosion by Mountain Glaciers

Plucking and Abrasion. — Glaciers accomplish their work of erosion in two ways. (1) The ice secures a hold on the material of its bed either by freezing about projecting points of rock or by being pressed into the joints and other cracks by its great weight. As the glacier moves on rock fragments are pulled out and carried along. This process is called *plucking*, and by it a glacier may remove a great quantity of material in much-jointed rock. The process, however, is of little effect on rocks which have few joints; and consequently one sometimes finds that a glacier has been able to deepen its valley more easily in hard granite and gneiss than in the softer limestone, because the former were much fractured, permitting the plucking out of blocks, while the latter being less broken was little affected. (2) Glaciers also deepen and widen their valleys by abrasion. The tools which accomplish the work of abrasion are the rocks which have been torn from the bed by plucking and those which have reached the base of the ice from the surface through crevasses. Holding these rock fragments in a firm grasp and pressing with great force, estimated to be 48,600 pounds to the square yard in portions of the Aar Glacier, a glacier acts as a gigantic file, cutting down projecting points, and deepening and smoothing its bed. The hard pebbles scratch and the bowlders groove the bedrock; while the clay and rock, ground fine by the process, polish the surface, producing the smoothed and striated appearance so characteristic of glaciated rocks.

FIG. 142. — Roche moutonnée, Bronx Park, City of New York. (U. S. Geol. Surv.)

It will readily be seen that a thick glacier, because of its great weight, will be able to erode its bed more rapidly than a thin one, and that a very thin glacier or one with clear ice at its bottom may, indeed, not only be unable to wear down its rock bed, but may even override loose sand or glacial drift.

In moving over a projection in its valley a glacier smooths off the side upon which it impinges (the *stoss* side) and plucks angular fragments from the *lee* side, often leaving it rough and jagged. It also smooths rough surfaces into forms (Figs. 142, 143) which, because of their rounded shapes, have been given the name *roches moutonnées* (French for rock sheep). If one looks *down* a glaciated valley, the smooth stoss slopes of the roches moutonnées are very striking. If, however, one glances *up* the valley, the rough lee sides of the roches moutonnées are often so conspicuous as to seem to contradict the statement that glaciers deepen their valleys by abrasion.

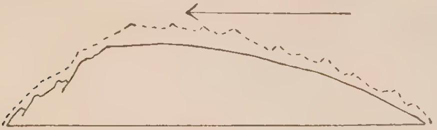


FIG. 143. — Diagram showing a projecting rock smoothed and rounded on the side upon which the glacier impinged (stoss), and roughened on the lee side by plucking,— a roche moutonnée.

Effect on the Material Carried. — Not only are the rock beds of glaciers grooved by bowlders, scratched by pebbles, and polished by clay, but these tools are, in turn, scratched and polished (Fig. 144). If one axis of a glaciated pebble is much longer than the other, it is usually found that the striations are parallel to the longer axis. This is due to the fact that the pebble was held in this position in the ice, as it offered less resistance in this way than in any other. If the axes of a pebble are approximately equal, it may have scratches running in many directions, as this shape would enable it to turn more easily in the ice and therefore to be carried onward in various positions.

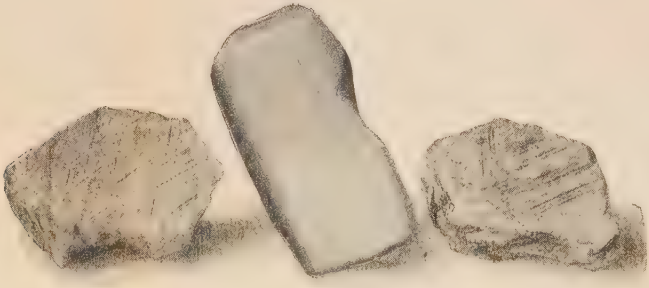


FIG. 144. — Glaciated pebbles. (The first and third after Blackwelder and Barrows.)

Since much of the rock of the valley floor over which a glacier moves as well as the pebbles which it holds in its grasp are ground to powder, it is not surprising to find the water of glacial streams so turbid with sediment as to be spoken of as *glacier milk*. The light color of such streams differs from the yellow color of ordinary streams because the former carry freshly ground, unoxidized rock, and the latter the products of weathering. The Aar Glacier, for example, a comparatively small glacier of the Alps, is estimated to discharge 280 tons of rock flour a day during a summer month.

Factors Influencing the Rate of Erosion. — As has been said, glaciers accomplish little erosion in passing over smooth surfaces. The amount of morainic material carried by Greenland glaciers, for example, is surprisingly small. This is due to the fact that they have moved over their beds so long as to render them comparatively smooth. If, however, a glacier moves over a bed whose surface is sufficiently rough to permit the ice to tear away fragments by plucking (p. 157), it is likely to deepen its bed rapidly, since under these conditions a large surface is exposed to the wear of the débris held in the base of the ice. Erosion is also favored by the incoherence of the material over which the ice moves, by the weight of the ice, and by a rapid rate of movement; but is unfavorably affected by an overloading of the basal portion of the glacier with débris and by the resistance of the rock.

DEPOSITS OF MOUNTAIN GLACIERS

Terminal Moraines. — At the lower end of a glacier, where the melting equals, or nearly equals, the advance, all of the débris (the superglacial, englacial, and subglacial) is deposited as a *terminal moraine*. Terminal moraines (Fig. 145) are usually crescent or horseshoe-shaped, concave towards the glacier, and often form conspicuous hills in valleys once occupied by glaciers. The heights of terminal moraines vary greatly, since the quantity of material deposited in them depends upon a number of factors. (1) The length of time during which the front of a glacier remained stationary is important. If a glacier advances 600 feet a year and for a number of years melts back at the same rate, it is evident that each year all of the débris carried on, in, and under it will be left at the same place, with the exception of that which is carried away by the stream which flows from it. If, on the other hand, the ice melts back 600 feet a year, while it advances 500 feet, it is evident that comparatively little débris will be left at any one spot, and no conspicuous hills or ridges will be formed. (2) The velocity of the glacier, (3) the quantity of material transported by it (p. 154), and (4) the amount carried away by the stream which flowed from its end are also determining factors in the size of terminal moraines. They sometimes reach a height of several hundred feet, but heights of 100 or 200 feet are more common. If the front of a waning glacier halts for considerable periods at different points, a series of terminal moraines (also called *recessional moraines*) will be left.

The material of terminal moraines usually consists of a heterogeneous mixture of large and small pebbles and bowlders of different kinds, embedded in clay and sand. Occasional patches of stratified sand and gravel from the water of the melting ice also occur. All the glacial débris is called *drift*, the unstratified is called *till* or *bowlder clay*, and the stratified (sorted and laid down in water) is called *stratified drift*.

Fig. 145. — Moraine near Dansville, New York. (Photo. H. L. Fairchild.)

On glaciers which move between precipitous walls supplying great quantities of talus, the lateral moraines will be large; and upon the disappearance of the ice, especially if the retreat be slow, a high ridge of unstratified drift will be left on each side of the valley. Some of these are a thousand feet or more in height. The terminal moraine of such a glacier may be comparatively insignificant. Terminal moraines are breached by streams and are sometimes entirely removed by them. Sometimes, however, the moraine constitutes an effective dam for many years, behind which a picturesque lake lies.

Thousands of mountain lakes owe their existence to such morainic dams.

Submarginal Moraines. — Another kind of moraine is formed under the sides of a glacier by the movement of the ice from the center to the sides. This should not be confused with the lateral moraines of the surface (p. 154). In valley glaciers which receive little superglacial débris these submarginal moraines may be thicker than the surface moraines. The presence of polished and striated pebbles and bowlders in such moraines is abundant proof that the drift composing them had been carried between the ice and its bed.

Ground Moraine. — A glacier may be so full of débris in its basal portion that it is unable to carry all of it. Under such conditions some of the load is deposited and is overridden. Such deposition takes place (1) where the ice is thinning near the end, as this makes its movement less rapid, so that it is unable to carry all of the load which it has acquired in its progress through a rough valley. Such deposition also occurs (2) after a glacier has passed over a projection in its bed, as the bottom of the ice is then heavily loaded with the débris which it has plucked or abraded from the obstacle.

In a valley formerly occupied by a glacier there is usually a layer of compact till composed of clay and much-worn pebbles. This deposit is known as the *ground moraine* and was derived either from the bottom of the advancing ice, as described above, or from the base of the ice upon its disappearance. It is usually thickest near the terminal moraine and thinnest near the head of the glacier, while over portions of the valley it may be entirely lacking. Since conditions in valley glaciers favor erosion rather than deposition, their ground moraines are seldom important, being in contrast in this respect to continental glaciers (p. 171), whose ground moraines are of considerable thickness, although seldom attaining the depth of terminal moraines.

The Work of Glacial Streams. — The streams which flow from beneath glaciers or from their sides are supplied with pebbles from the moraine and an abundance of rock particles derived from the rock ground to fine flour between the ice and its bed. With such tools they are able to deepen their channels as long as they have sufficient velocity. The streams from certain glaciers emerge from their fronts in deep gorges which they have cut in the rock. The Lämmer Glacier of Switzerland and the Mer de Glace are examples. It is doubtful, however, if the deepening which is such a marked feature of valleys long occupied by glaciers, has been accomplished to any great extent by subglacial stream erosion.

If the streams which issue from glaciers are ponded by terminal moraines, lakes are formed in which they deposit their loads. If they have a free course, however, they will carry their loads of rock flour and pebbles farther down the valleys. The coarse gravel will soon be dropped, but the finer material may be carried some distance. When, however, a stream thus loaded reaches a more gentle grade, it may lose so much velocity that it becomes overloaded and compelled to take a braided course (p. 86). The stratified deposits laid down in valleys by glacial streams are called *valley trains* (p. 178).

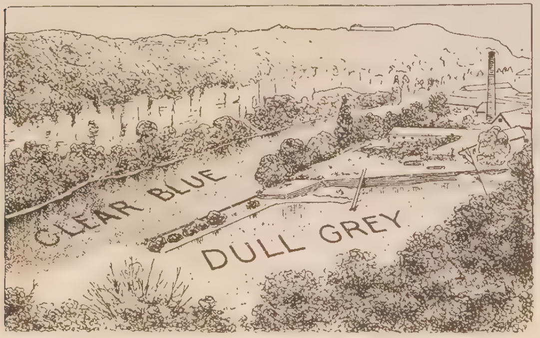


FIG. 146. — The union of the Rhone and Arve rivers near Geneva, Switzerland. The water of the Rhone, having been filtered by Lake Geneva, is clear and blue, while that of the Arve is grey with the rock flour carried into it by glacial streams. To the right is seen the cement works for recovering the Arve sediments. (Hobbs, *Earth Features*.)

As has been stated (p. 159), streams flowing from glaciers are milky with rock flour, while those which gather their water from the land surface may be yellow with the clay of the weathered rock which they bear along, but streams filtered by lakes are clear. At the confluence of the Rhone and the Arve (Fig. 146) a striking contrast is seen between the clear water flowing from Lake Geneva and the turbid water of the Arve which has its source in the glacier of that name. For a

FIG. 147. — Block diagram showing a valley blocked by a moraine; the stream having been diverted from its old course has cut a steep-sided, postglacial gorge.

short distance after their union the waters of the two streams flow side by side, but gradually they merge.

Since streams are no longer overloaded after the retreat of their glaciers, they begin to erode the alluvial deposits of their former flood plains and in this way form the terraces which so often border stream valleys in glaciated regions. As the streams deepen their beds in their partially filled valleys, they occasionally fail to find their former channels, and after excavating broad valleys in the recently deposited gravels may cut narrow gorges into solid rock. This is shown in the diagram (Fig. 147), in which a stream flows from its alluvium-filled valley (in the background) into a deep, postglacial gorge in the foreground.

LANDSCAPE MODIFIED BY GLACIAL ACTION

Characteristics of Glaciated Valleys. — A striking feature of mountain valleys which have been subjected to the long-continued erosion of thick glaciers is the flatness of the floors and the steepness of the valley sides, as contrasted with the V-shaped valleys cut by streams. A cross section of a valley which has been shaped by glaciers is typically a gigantic U, sometimes more than 3000 feet deep and three miles wide. The tributary streams of such valleys usually enter them over falls. The high, tributary valleys are called *hanging valleys* (Fig. 148), and their occurrence is proof that the main valley has been deepened by glacial action.

This peculiar relation between the main valley and its tributaries can best be understood by following the history of a valley from the time it was first occupied by a glacier until it again became free from ice. When a main valley is occupied by a thick glacier, it will in time be deepened and broadened, especially near the bottom, and the valley sides will at the same time be *oversteepened*. This excavation is termed *overdeepening*. Since the main valley is well filled with ice, it is evident that the glaciers of the tributary valleys will not be able to lower their beds far below the surface of the main glacier. Consequently, when the glaciers disappear from the valleys, the side valleys will no longer enter the main valley at grade, but by falls. In other words they have become hanging valleys. In this way those steep-sided, picturesque valleys were formed for which Switzerland and British Columbia are famous. The many falls of the valleys of the Yosemite, California (Fig. 148), and Lauterbrunnen,

Fig. 148. — Yosemite Valley, California. This magnificent valley owes its shape in large measure to glaciation. At the right is a hanging valley from which a cascade falls into the main valley.

Switzerland, and many other of the high falls of the world are of this origin. Hanging valleys of a different origin have been discussed elsewhere.

The courses of valleys are straighter after glaciation than before. This is due to the fact that the glaciers, because of their rigidity, cut off the " spurs " on the inside of the curves.

The line on the side of a U-shaped valley above which glacial erosion was not effective is marked by a change in slope, forming a sort of " shoulder." Such " shoulders " are of some economic importance in Switzerland, since they usually afford good pasturage and are favorite spots for hamlets, as they are not subject to the severe cold of the deep valleys. The " shoulders " are usually about 1000 feet above the bottom of the valleys in the Alps, but are sometimes as much as 3000 feet above.

Mature Glaciated Valleys. — It is evident that valleys which were formerly occupied by glaciers will not be U-shaped unless the glaciers were at work for a long time, and every gradation can be seen between them and V-shaped valleys, in which the inside of the curves (spurs) have been little cut away and the beds are still broken by falls. In valleys long subjected to glacial action the spurs are cut away, the bottoms widened, and the sides smoothed. In the upper and middle portions where the weight of the ice and its movement were greatest, basins may have been formed in which lakes now rest. Lake Chelan, Washington, is probably such a lake, as are also the beautiful lakes of the Scottish Highlands. Even maturely glaciated valleys may not have graded beds, since, under certain conditions (p. 157), a glacier erodes one portion of its bed more deeply than another.

Destruction of Features of Glaciated Valleys. — The characteristic features of glacial valleys are destroyed in process of time by the work of erosion and weathering, very much as are those of cirques. Talus slopes accumulate at the bases of the cliffs ; landslides sometimes cover considerable areas of the bottoms with débris ; the streams from the mountains build out alluvial fans and cones ; and in the course of time the " shoulders " are worn away by weathering and the action of the rills which tumble over them. The streams from the hanging valleys cut down their beds so that they enter the main valleys through deep canyons. It is possible by these criteria roughly to determine the length of time since the disappearance of the glacier from the valley.

Fiords.[1] — The coast of Norway is noted for the long, narrow bays, called *fiords* (Fig. 149), which may be navigated for many miles.

Fig. 149. — Fiord, Grenville Channel, British Columbia. (U. S. Geol. Surv.)

Into these fiords streams enter from hanging valleys over falls. Soundings show that while the end towards the sea is very deep, it is not so deep as at some distance inland. The maximum depth of the Sogne fiord in Norway (Fig. 150) is 4000 feet, and that of three others is 2550, 2298, and 1800 feet. The greatest depth occurs where the fiord is bounded by mountain masses of great extent and elevation.

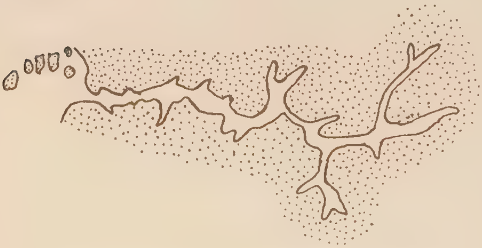


Fig. 150. — Map of Sogne fiord, Norway.

There seems little doubt that fiords are valleys which were greatly deepened by glacial erosion. Their increased depth from the outlets inward is due either to the greater erosion of the glaciers some distance inland, where they were presumably thicker and their erosive power consequently greater; or to the piling up of morainic matter where they entered the ocean; or probably both coöperated to produce the result. Whether or not the glaciers actually cut the valleys below sea level has not been proved.

---

[1] It has been maintained that fiords owe their characteristics to earth movements and not to glacial action, and, in fact, that fiords occur in non-glaciated regions. According to this theory areas were fractured along certain belts as they were being raised to form plateaus. These belts of more or less shattered and fissured rocks are supposed to have subsided, with the formation of steep-sided troughs. In support of this theory it is pointed out that fiords are arranged along a kind of angular network believed to be caused by intersecting lines of fractures. (Gregory, J. W., — *The Nature and Origin of Fiords,* 1913.)

During the process of the glacial deepening of the Scandinavian fiords the land was higher than now. This was followed by a period of great submergence and later by a reëlevation of a few hundred feet. Fiords are common in Greenland, Alaska, British Columbia, southern Chile, and Patagonia.

Piedmont Glaciers

When mountain glaciers reach the plain at the foot of the mountains from which they flow, they spread out, as they are no longer confined by valley walls, and coalesce to form *piedmont* (foot of mountain)

Fig. 151. — Model of the Malaspina Glacier. The dark margin is the moraine-covered area upon which a forest of spruce, cottonwood, and alder grows. (Model by Lawrence Martin. Copyright, University of Wisconsin.)

glaciers. A typical example of such a glacier is the Malaspina in Alaska (Fig. 151). It is formed by the union of several glaciers which move down the valleys of the St. Elias range upon a nearly flat plain. The area of the united glacier is nearly 1500 square miles, about the size of Rhode Island. The outer margin where the ice is probably 1000 feet thick is covered with a belt of morainic matter a few feet thick and several miles wide, on which grows a luxuriant vegetation. Extensive areas of bushes are found and, near the outer edge, trees some of which reach a diameter of three feet. On the surface of the nearly stagnant glacier are numerous ponds in which stratified deposits are laid down. The central portion of the glacier is comparatively free from débris and is much broken by crevasses into which streams from the melting ice flow. Piedmont glaciers are rare at the present time, but were much more numerous during glacial times, when they existed at the foot of the Alps, at the foot of the mountains of western North America, in the southern Andes, and elsewhere.

CONTINENTAL ICE SHEETS

Up to this point mountain glaciers have been discussed because, on account of their small size and accessibility, they are more easily studied and their phenomena are better known than are those of the great continental glaciers such as now cover Greenland and the Antarctic Continent. At one time ice sheets covered the northern portions of North America and Europe. These were of great extent, those of North America covering an area estimated at 4,000,000 square miles; of long duration, and probably of great thickness. The stratified and unstratified drift so conspicuous in many of these once glaciated regions was formerly believed to have been transported to its present position and the underlying rock scratched and polished, by a great flood (Mosaic flood) which swept down from the north, carrying with it pebbles and bowlders which striated and grooved the rocks over which they were borne. The term *drift* is a relic of this ancient theory. One cannot obtain a clear conception of the conditions which existed in North America and Europe during the Glacial Period (p. 645) without a study of the existing continental glaciers of the polar regions.

Greenland. — Greenland is a continent 1400 miles long and 900 miles wide. Of this area, fully three quarters is covered at all times with ice, the only inhabited portion of the continent being a narrow strip of land along the coast, generally from 5 to 25 miles wide (Fig. 152). The great snow desert of the interior is devoid of life, with the exception of lowly forms, such as the microscopic red plants (*Sphærilla nivalis*) which sometimes exist in such abundance as to give a red color to the snow and produce the "red snow" of both mountain and continental glaciers.

FIG. 152.—Map of Greenland, showing a continental ice sheet.

All Greenland explorers give nearly identical descriptions of the interior. Near the coast the ice sheet rises with comparative abruptness, being steeper on the east than on the west coast, while the central portion is nearly flat (Fig. 153). The gradient of the surface, as a whole, gradually decreases as the interior is approached, and "the mass thus presents the form of a shield with a surface corrugated by gentle, almost imperceptible undulations, lying more or less north and south." (Nansen.) The highest recorded point in the interior is about 9000 feet above the sea, although it is possible that unexplored portions may reach an altitude of 10,000 feet. A hundred miles from the coast no depressions or elevations in the ice mark the presence of valleys or mountain ranges beneath; but within 50 or 70 miles of

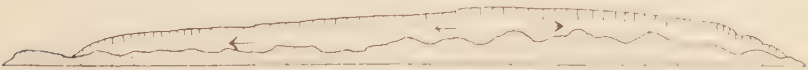


FIG. 153.—A section across Greenland, showing the profile of the ice and the probable configuration of the land.

the coast broad, shallow, basinlike depressions appear which, when followed seaward, grade into great glaciers which flow from the central mass into the sea through valleys. The scenery of these broad depressions resembles, on a grand scale, the gathering grounds of Alpine glaciers. The ice of the depressions which give rise to these separate tongues of ice is probably a mile in thickness,[1] but on the mountain ridges it is much thinner.

The smooth almost flat central portion gives place near the margins to a surface of a decidedly different character. Here, where the motion of the ice is more rapid, being greater in one portion than in another, the surface is much broken by crevasses which make travel well-nigh impossible. Near the coast, where the mountains protrude through the ice as islands (*nunataks*), the whiteness of the surface is broken by patches and lines of rock waste derived from these projections. Nunataks are often surrounded by deep ditches, due to the absorption of the sun's heat by the dark rock walls and its radiation from them, with the consequent melting of the adjacent ice.

As has been said, the great interior plateau is drained by glaciers which descend through valleys. Many of these reach the sea, where their fronts are broken off and carried away as icebergs. Some of these glaciers are among the largest known. One of the most remarkable is the Humboldt Glacier, which has a breadth of more than 50 miles where it enters the ocean. Its front rises precipitously from the level of the water to a height of 300 feet, and the total thickness above and below the water level at this point is probably 2700 feet. Some of these glaciers fail to reach the sea but spread out on flat plains. In such glaciers it is seen that the ice is stratified and that the white upper layers are in marked contrast to those near the base, which are often so filled with débris that it is difficult to tell where the ice ends and the ground moraine begins. This loading of the basal portions of the ice and the almost total freedom of the surface from débris should be borne in mind when the work of the ancient ice sheets is considered.

The rate of movement of the Greenland glaciers near their ends is sometimes more than 50 feet a day, but in the interior of the ice sheet the rate may be as slow as an inch a day or practically zero; in other words the motion is from the center of the ice sheet outward, the movement being caused by the weight of the ice. Moreover, the

---

[1] Geikie A., — *Textbook of Geology.*

movement is locally concentrated and therefore increased where the ice finds a relatively narrow outlet between inclosing ridges.

The contour of this buried continent can be conjectured from the fact that the greatly indented coast with its numerous islands resembles that of Norway, so that it is probable that a rough, mountainous surface like that of Norway underlies the ice.

The Antarctic Continent. — The Antarctic Continent is larger than the whole of Europe and differs from Greenland in its greater height, in the greater severity of its climate, and in the absence of a strip of ice-free land bordering the ice. The interior, as in Greenland, is dome or shield-shaped and was found by Amundsen to be 10,500 feet above the sea at the pole. Above the general level of the shield, mountains rise to heights of 15,000 feet. The excess ice is drained by valley glaciers, as well as by the Great Ice Barrier, a floating ice shelf which in Victoria Land forms an ice cliff many miles long and varying in height from 280 feet to places so low that it can be used as a wharf.

ANCIENT GLACIATION

The proofs that glaciers at one time covered a large area in North America are so conclusive and the belief is now so universal that it seems remarkable that the theory was not advanced until 1846 (by Agassiz), and that nearly thirty years elapsed before its general acceptance by geologists.

DEPOSITION

(1) **Bowlders.** — One of the most striking proofs that a region has been covered with glaciers is to be found in the occurrence of bowlders in the soil and on the surface, which differ in composition from the underlying rock and consequently were not derived from it. When traced to their parent ledges, some of these bowlders are found to have been carried several hundreds of miles over hill and dale. In regions of rough topography, glacial bowlders are often found at a much higher level than the ledges from which they came. For example, bowlders of quartzite have been found on Mt. Greylock, Massachusetts, which must have been carried into a valley and then to the top of the mountain, a vertical distance of almost 3000 feet. Bowlders of jasper conglomerate, composed of bright red pebbles of jasper embedded in white quartz, have been found from the northern

to the southern confines of Ohio, and when traced northward are seen to have been derived from a deposit on the north shore of Georgian Bay in Canada. Native copper from the copper deposits of Lake Superior has been found in the drift many miles to the south. Pieces of copper transported in this way were often picked from the drift and made into ornaments by the ancient mound builders. In New England trains of bowlders have often been traced to outcrops which have some distinctive character (Fig. 154). In any one deposit the number of kinds of rock is usually not very great, although in some cases one may find as many as twenty different varieties in a single bed of till. The bowlders are often angular and scratched, and in both of these features differ from stones which have been rolled about by streams. It should not be inferred from the above that no rounded and unscratched bowlders occur in glacial débris, for sometimes the angular and scratched bowlders are in the minority.

FIG. 154. — Map of the "bowlder train" from Iron Hill, Rhode Island. The direction of the movement of the ice is generalized. (After Hobbs.)

(2) **Unstratified Drift.** — As has been said in connection with mountain glaciers, all of the débris transported by the ice is included under the general term *drift; till* or *bowlder clay* being the unstratified drift, and that carried and later deposited by streams being called stratified drift (p. 178). Till (Fig. 155) is composed of a heterogeneous mixture of bowlders of many sizes embedded in clay. The mixture of coarse and fine material and the lack of stratification proves without question that such deposits were not made by streams. The stratified drift (Fig. 156) was deposited by melting waters under various conditions. Drift is not confined to the valleys of glaciated regions but is spread over hills as well, being in a measure independent of topography.

The deposition of drift may render a region either rougher (Fig 157) or smoother (Fig. 158). If, for example, in passing over a region somewhat cut up into valleys, the ice sheets filled them with drift, compelling the streams upon the retreat of the ice to make new valleys, the result may be a smoother surface. Many portions of the northern United States have been modified in this way. On the other hand, the irregular dumping and piling up of drift in moraines may roughen the landscape. The northern half of the peninsula of Michigan, which in certain places now rises from 1000 to 1100 feet above the surface of the Great Lakes, seems to have no rock standing more than 250 to 300 feet above the lakes, there being from 700 to 800 feet of drift on its higher parts. The average thickness of the drift in southern Illinois is somewhat less than 30 feet; in northwestern Ohio, northern Indiana, and

Fig. 155. — Till. Note the heterogeneous mixture of large and small bowlders and fine clay. (Pennsylvania Geol. Surv.)

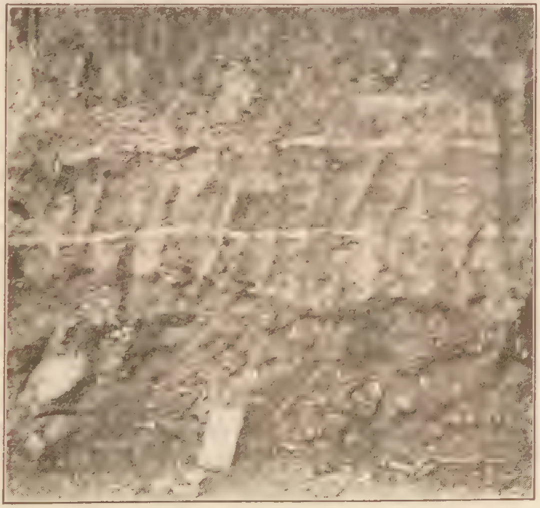


Fig. 156. — Stratified lake clay resting on till.

northeastern Illinois the average is almost 200 feet, and in the southern peninsula of Michigan about 300 feet. Borings near Cleveland, Ohio, show that the drift extends 470 feet below lake level.

FIG. 157. — Diagram showing a region made rougher by glaciation.

The drift deposited under the ice was often compacted by the great weight of the ice mass into a dense bowlder clay which is excavated with difficulty.

Mention should be made of an area in Wisconsin and adjacent portions of Iowa, Illinois, and Minnesota, which was not covered by the ice sheets, the *driftless area* (Fig. 159 *A*). In this area the rock is deeply weathered, and rock pillars are not uncommon; the drainage is perfect, the streams being without swamps, lakes, or waterfalls. It differs markedly in these respects from the adjoining regions (159 B). This freedom from ice was due to a combination of causes: its position with reference to the centers from which the ice moved, the higher ground to the north, and the presence of the deep Michigan and Superior basins which diverted the flow of the ice.

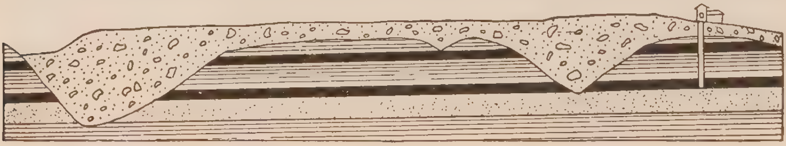


FIG. 158. — A region made smoother by glacial débris. The uncertainty in coal mining (black bands) in such a region is shown.

Moraines. — The drift was laid down either as terminal, ground, or lateral moraines, or as stratified deposits.

(*A*) *Terminal moraines* (see p. 159) were formed where the ice front remained stationary or nearly so, for a long time, so that its forward movement was almost or quite equal to the melting at its margin, sometimes being slightly in excess and sometimes slightly less. Under such conditions it will readily be seen that the glacial débris would be left in extremely irregular deposits, unless the drift had been uniformly distributed throughout the ice, which apparently was seldom the case. The term "recessional moraine" is often used to indicate those moraines which were formed during the various halts of the ice as it retreated to the north, "outer terminal moraine" being reserved for the moraine formed at the time of the greatest extension of the ice. In this discussion the term "terminal" will be used to include both. "The surface of these moraines (Fig. 145, p. 160) is a jumble of elevations and depressions, which vary from low, gentle swells and shallow sags to sharp hills a hundred feet or so in height, and deep, steep-sided hollows. Such tumultuous hills and hummocks, set with depressions of all shapes, which are usually without outlet and are often occupied by marshes, ponds, and lakes, surely cannot be the work of running water. The hills are heaps of drift, lodged beneath the ice edge or piled along its front. The basins were left among the tangle of morainic knolls and ridges as the margin of the ice moved back and forth. Some bowl-shaped basins were made by the melting of a mass of ice left behind by the retreating glacier and buried in its débris." (Norton.)

Moraines of the Last Great Ice Sheet in North America. — These moraines usually occur in belts three to ten or fifteen miles in width, their position being marked in Minnesota, Wisconsin, and other states by thousands of lakes. In regions of little topographic relief moraines may be the most conspicuous features of the landscape. Some of the moraines have been traced several hundreds of miles and if the correlations are correct have been identified over a distance of a thousand miles or more (Fig. 160).

Fig. 159. — *A* shows the drainage of a portion of the "driftless area" indicating that it had a normal development. It is in decided contrast to the adjoining glaciated area *B*

At its greatest extent (Fig. 565, p. 646) the ice may have stretched on the east as a great wall from Massachusetts to northern Labrador, discharging icebergs throughout its length. The terminal moraine forms the backbone of Long Island and stretches across northern New Jersey. From there its direction is northwest to the state of New York and from there to the southwest as far as northern Kentucky and almost to the southern tip of Illinois. From Kansas it extends a little west of north into North Dakota, from which point it has a general east and west direction except in the mountainous regions.

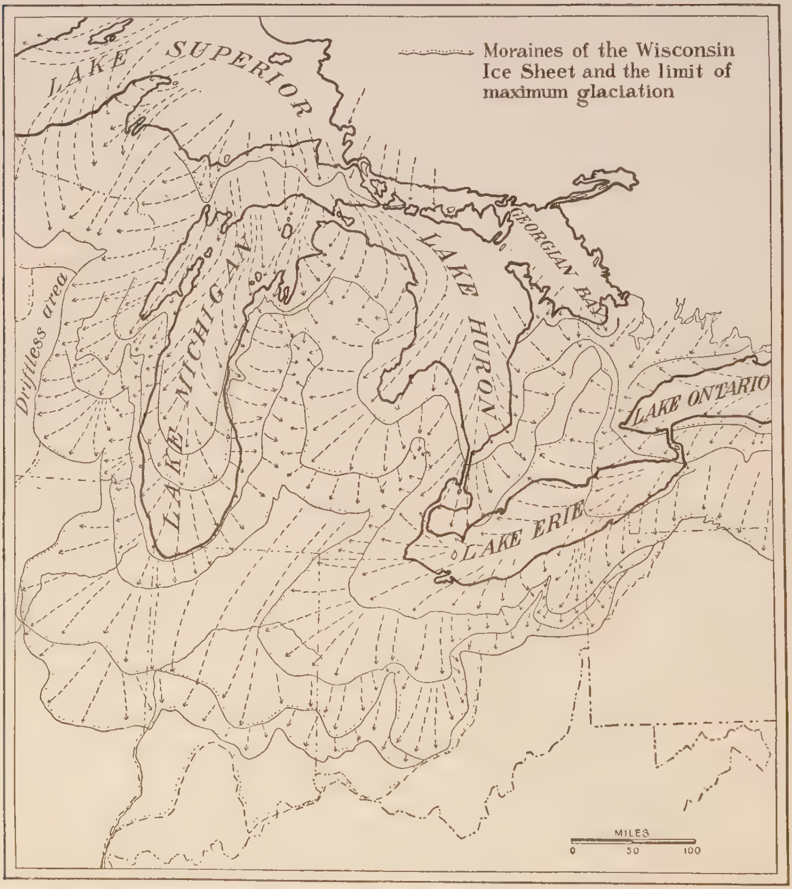


Fig. 160. — Map showing moraines and direction of ice movement (indicated by arrows) of the last continental ice sheet. The lobate character of the moraines is pronounced. The "driftless area" was not covered by ice. (After U. S. Geol. Surv.)

(*B*) *Ground Moraine.* — The till which covers regions between moraines and which constitutes by far the largest area of the glaciated surface is called the *ground moraine.* Its topography varies widely, being usually rolling and interspersed with swamps, but sometimes nearly flat over large areas. The ground moraine is of variable thickness, being thinner in Canada (Fig. 161) than in the United States, since the ice in its movement to the south carried away much of the material derived from the underlying rock, leaving little to be deposited on the melting of the ice.

FIG. 161. — Map showing the effect of glaciation in different parts of North America. The area of maximum deposition lies chiefly south of the Great Lakes, where the ice was relatively thin and its erosive power was generally feeble. (Modified after Dryer.)

Drumlins, where they occur, are conspicuous features of the ground moraine. These are smooth, elliptical hills composed of till and have their longest axes parallel to the movement of the ice (Fig. 162). They are not by any means found everywhere in the ground moraine, but are abundant in portions of central and western New York, Wisconsin, eastern Massachusetts, and elsewhere. The islands in Boston Harbor are drumlins. There is still much doubt as to the precise

FIG. 162. — Drumlins. Wayne County, New York. (Photo. H. L. Fairchild.)

mode of their formation, but there is abundant evidence that they were developed beneath the margin of the ice and were built up by the addition of successive layers of till.

Stratified Drift. — An estimate[1] has been made, based upon a study of the Malaspina Glacier of Alaska (p. 168), that at certain stages of the withdrawal of the great ice sheets the Mississippi River had a volume sixty times greater than at present. When one considers the number of streams flowing on, under, and in front of the ice, whose combined volumes made the greater rivers of the time, we can understand the abundance of stratified deposits, such as kames, eskers, deltas (laid down in temporary lakes), outwash plains, and like deposits, so common in the glaciated portions of North America.

Outwash Plains. — The streams which flowed from the fronts of the continental ice sheets were usually heavily charged with silt, sand, and gravel, which they obtained from the ground and terminal moraines (p. 175), so that they were able to aggrade their beds, often leaving thick deposits. If they flowed through well-defined valleys, the loads were deposited in the valley bottoms and formed *valley trains*. If a number of streams issued from the ice front on a plain, or in a shallow valley, they gradually raised its level as they deposited their surplus loads. In this way the streams quickly built their beds above the level of the surrounding regions and were in consequence forced to shift their positions to lower places, forming braided streams (p. 86). When valley trains grew to such an extent that they overlapped, an *outwash plain* resulted (Fig. 163), much as

FIG. 163. — Outwash plain. New York. (Photo. H. L. Fairchild.)

---

[1] O. D. von Engeln.

FIG. 164. — Kettle holes. (After C. R. Dryer.)

alluvial slopes are formed from the growth of adjacent alluvial fans (p. 124). Outwash plains differ from valley trains in being shorter and wider.

Outwash plains are closely associated with terminal moraines. The longer the front of a glacier remained stationary, the more favorable were the conditions for the accumulation of gravel, since the streams then had an abundant supply of débris which they continued to deposit. The material of outwash plains and valley trains is sand and gravel, the coarser material being nearest the moraine and the finer further away. Outwash plains may be very extensive, and since they are composed of sand and gravel are usually infertile, sometimes to such a degree as to form miniature deserts. The sandy, desert-like plain south of the terminal moraine on Long Island is an outwash plain.

Outwash plains and morainic plains may be "pitted"; that is, the general level may be broken by more or less rounded depressions. These pits are called *kettle holes* (Fig. 164) and were usually developed from the melting of blocks of ice which had been buried in the drift as the ice retreated. In the outwash plain of the Hidden Glacier in Alaska kettle holes are seen to be forming; and "their development is due to the melting out of ice from beneath the plain, although in no case was the ice actually seen." (Tarr.)

Terraces. — The valleys of the rivers of Ohio, Indiana, and Illinois which carried off the water of the melting ice are now bordered by terraces of stratified drift, and the conspicuous terraces of the Connecticut and Merrimac rivers (p. 127) and their tributaries are remnants of deposits of stratified drift laid down either by overloaded glacial streams or by streams which were overloaded as a result of the erosion of till soon after it was uncovered by the ice.

Deltas. — When glacial streams entered bodies of water they rapidly built out deltas (Fig. 122). Ancient deltas of this origin often afford the best evidence of the former existence of a glacial lake. In western Massachusetts, for example, a glacial lake of large extent was formed by the damming of the Hoosic River by the ice sheet. Although it did not exist a sufficient length of time to permit the waves to cut back the shores to form cliffs, yet the heavily loaded streams which flowed into it built conspicuous deltas.

Eskers. — Eskers (Fig. 165) are narrow, usually winding ridges of gravel and sand, ten or more feet wide at the summit and from a few feet to fifty or more feet high, and resembling abandoned railroad grades. They usually follow valleys but sometimes extend across the country with little regard to the topography, even when the hills stand 200 or more feet above the valleys. Single esker ridges in Ireland, Scandinavia, Finland, Maine, and elsewhere have been traced many miles. Usually, however, they are less than a mile in length.

Eskers are believed to have been formed beneath glaciers by subglacial rivers which flowed in tunnels beneath the ice, and are most

FIG. 165. — The long, narrow, winding ridge is an esker. It is composed of stratified sand and gravel. (Photo. F. B. Taylor.)

abundant where subglacial streams emptied into bodies of water. Under such conditions the outlet of the stream from the glacier would be more readily closed by the delta which formed rapidly where the sediment was dropped as the stream emerged from the ice into the lake, and the tunnel under the ice would thus be gradually filled with sand and gravel. Most eskers were probably formed, for the most part, in connection with the melting of stagnant ice, since it is evident that had the ice been even in slight movement the winding ridges would have been destroyed.


FIG. 166. — Kame. North Adams, Massachusetts. Kames are composed of sand and gravel, and consequently are always characterized by rounded slopes.

Kames. — In glaciated regions groups of sand and gravel hills and ridges, as well as isolated, conical hills with high and steep sides, are not uncommon. These hills of stratified drift are called *kames* (Fig. 166). They are often confused with eskers and indeed the two are, in individual cases, so closely associated and shade into each other so perfectly that it is difficult to state whether the deposit is a kame or an esker. Kames are composed of stratified sand and gravel, while drumlins (p. 177) are composed of till. They are often excavated for building and road material, and are favored sites for cemeteries. The same origin cannot be assigned to all the deposits that are classed as kames. Some were formed at the margin of the ice, where the streams issuing from beneath under pressure heaped up their loads against the ice front. Upon the melting of the ice these deposits assumed a more or less irregular surface, depending upon the character of the ice front. Kames of this origin are especially common near terminal moraines, and some of the conspicuous knolls and hills of moraines are often, individually, kames. Isolated kames may have been formed from the deposits of small lakes resting in depressions on the surface of the glacier. As the ice melted these would form mounds. Sand and gravel carried into moulins (p. 149) whose sub-glacial passage had been closed would produce such hills. When stagnant ice occupies deep valleys, drainage along the sides may give rise to large deposits of sand and gravel, which may be left in somewhat the form of a terrace with a kame topography when the ice has disappeared. Outwash plains and valley trains sometimes begin in kame areas.

Relation between Stratified and Unstratified Drift. — It should not be understood that stratified and unstratified drift always have topographic forms which distinguish them, or that they can always be clearly separated. The mingling of the unstratified and stratified deposits (Fig. 167) is readily comprehended when it is remembered that the edge of the ice sheet probably seldom remained in the same position long, but oscillated back and forth during its advance and retreat. In this way till has been covered with sand and gravel which in turn has been overridden by the ice and covered with till. Moreover, when temporary lakes existed between the ice front and its moraine, stratified deposits were laid down in the midst of the unstratified.

FIG. 167. — Diagram showing the relation between stratified and unstratified drift. (After U. S. Geol. Surv.)

EROSION BY CONTINENTAL GLACIERS

The amount of erosion formerly ascribed to continental glaciers was probably excessive. There is no doubt that the ice sheets modified the topography over which they passed, — in some cases profoundly, — but in general the more pronounced features of the landscape were little changed by erosion, although large areas were altered to a greater or less degree by the irregular deposition of drift.

Effect on the Underlying Rock. — Previous to the appearance of the continental ice sheets the surface of the rock of North America was deeply weathered (p. 651), much as it is now in the southern states. Consequently, when the ice covered and moved over this "rotten" rock (p. 27) and soil, it found an abundance of material which it carried along for a time and later dropped, either as heterogeneous, unstratified till, or as stratified sands, clays, and gravels. The rock underlying the drift is often smoothed and striated (p. 157) (Fig. 168), differing from that of the non-glaciated regions in this particular, as well as in the fact that the surface rock is usually fresh and does not pass gradually into soil, as the rotten rock has been removed by the glaciers. The scratches and grooves (Fig. 169) on the surfaces of glaciated rocks usually have a common direction (with some variation) and show, as do the glacial bowlders or erratics (p. 156), the direction of the movement of the ice. Harder portions of the rock being less easily smoothed by the ice, project slightly above the general surface and also show by the greater abrasion on one side (stoss) the direction from which the ice came. The effect of erosion on different kinds of rock is not always in proportion to their softness, although the softer the rock the more easily it will be worn away. More material may actually be removed from a hard but much-jointed granite by the

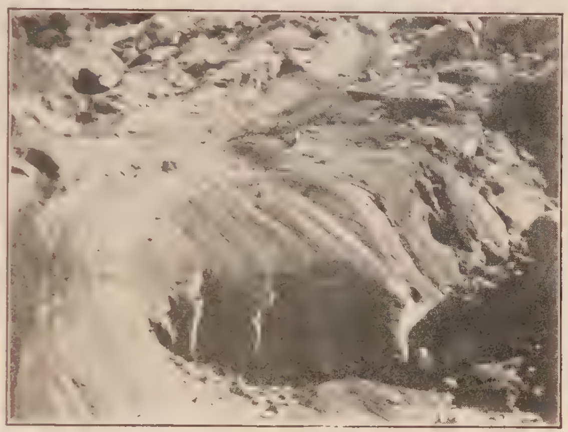


Fig. 168. — A rock surface polished and striated by glacial action. (Photo. L. E. Westgate.)

Fig. 169. — Rock grooved and polished by glaciers. The excavation on the right is artificial.

" plucking " of the blocks of the rock than is removed from a soft limestone in which joints are poorly developed (p. 157). Under certain conditions glaciers may have little effect on the underlying formations, as is shown by till and even sand and clay deposits (Fig. 170) laid down by an earlier ice sheet, which were but slightly affected when overridden by a later ice sheet. In Switzerland glaciers have overridden Alpine landslides without carrying away many blocks. It is possible, however, that such unconsolidated deposits as those just described were frozen when the ice moved over them.

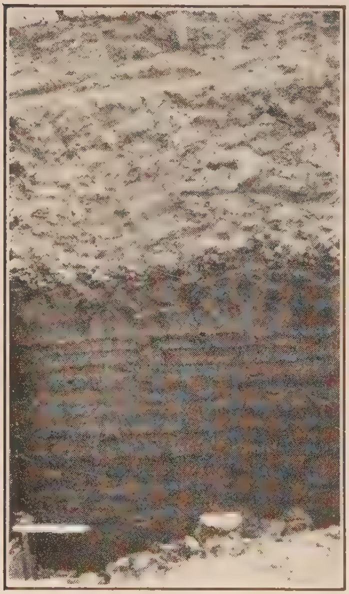


FIG. 170. — Till overlying lake clays, showing that a lake first existed and that the ice sheet advanced over the clays without being able to remove them. Williamstown, Massachusetts.

Modification in the Shape of the Hills. — The shape of the hills in glaciated regions sometimes shows the direction from which the ice came, the side upon which the ice impinged, called the stoss side, having a more gentle slope than the other, the lee side (Fig. 171). Hummocks of rock eroded by glaciers and known as roches moutonnées (p. 158) are well-developed in many places, but may be especially well studied in portions of Canada.

Effect of Glaciation on Drainage. — In general it can be said that glaciation tended to disturb the preëxisting drainage, with the result that land which in preglacial times was as thoroughly drained, for example, as portions of West Virginia and Kentucky to-day, became swampy, with abundant lakes and ponds.

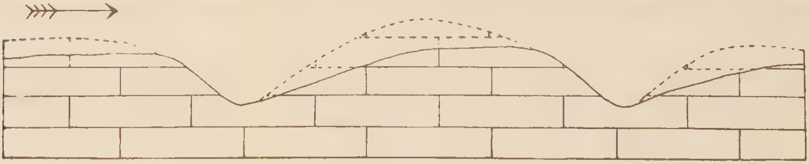


FIG. 171. — Diagram showing the effect of glacial erosion. The stoss side suffers more than the lee side, and the slopes are more gentle. The direction of ice movement is shown by the arrow.

1. Lakes and Ponds. — A glance at any good map of the United States shows that south of the limit of glaciation lakes are almost absent except (1) those formed by rivers in their meanderings (p. 120); (2) those in limestone regions (*e.g.*, Florida) (p. 69); and (3) those formed by wave and current action along the coast (p. 220). This condition is in decided contrast to that in the glaciated portions (Fig. 172). The depressions in which lakes and ponds occur were

FIG. 172. — Map showing the great abundance of lakes in a portion of a glaciated region. Ashby Quadrangle, Minnesota.

FIG. 173. — The Fulton chain of lakes in the Adirondacks, New York. First, Second, Third, Fourth, Fifth, Sixth, and Seventh Lakes are evidently the result of the partial filling of a preglacial river channel with glacial drift.

Fig. 174. — Lake Märjelen, formed by the damming of a valley by the Aletsch Glacier.

formed in several ways. The rock may have been scooped out by glaciers, forming *rock basins* (p. 145). Many such exist in mountainous regions affected by glaciation. River valleys may have been dammed by drift so as to form large lakes, such as Lake Geneva and Lake Constance in Switzerland. The many lakes which add so much to the attractiveness of the Adirondacks are the result of the repeated damming of old river courses (Fig. 173). The uneven surface of the drift is often dotted with lakes and ponds which rest in the inequalities formed by the irregularly deposited material. Basins may be produced by a combination of the above methods. The finger lakes of central and western New York (Cayuga Lake and Seneca Lake), Lake Chelan, Washington, and Lake Como, Italy, are the result of the deepening of old river valleys which lay in the direction of the movement of the ice and of the damming of their outlets. The bodies of water thus formed are long and remarkably deep. Many temporary lakes were formed between the ice front and moraines and also where glaciers moved up a slope, thus preventing the waters from taking their natural course. Glacial Lake Agassiz is such an example (p. 656). Valley glaciers sometimes dam their tributary valleys, thus forming lakes in them. Lake

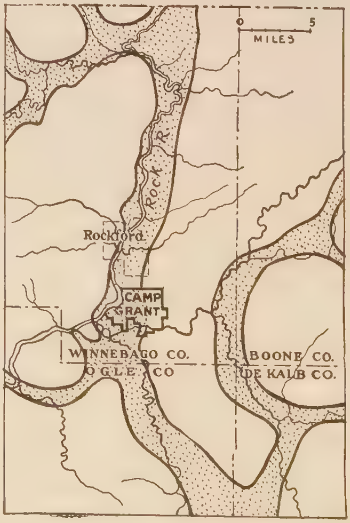


Fig. 175. — Map showing the preglacial course (shaded) of Rock River, Illinois, and the present drainage. (U. S. Geol. Surv.)

Märjelen, Switzerland (Fig. 174), owes its existence to the dam formed by the Aletsch Glacier.

2. *Rivers.* — To form a conception of the effect of glaciation on a well-drained region, imagine a mature country, such as portions of West Virginia (Fig. 95, p. 110), invaded by glaciers advancing from the north. It is evident that the north-south valleys would be the ones most likely to be deepened, since they are in the direction of the movement of the ice, and that the east-west valleys would probably be entirely or partially filled with drift, leaving basins which would be occupied by lakes upon the disappearance of the ice. In many cases, the streams would keep their old, wide, preglacial courses for a portion of their length, but in other parts would occupy deep, narrow, rock gorges which they had eroded after they were forced out of their old channels and had cut down through the drift (Fig. 175).

Waterfalls and rapids often occur at the points where streams have been diverted from their old channels by drift (p. 163). Many of the manufacturing centers of New England and other northern states owe their establishment to the existence of such natural water power.

Fig. 176. — Map showing the present course of the Ohio River and the course which it had previous to glacial times (shown by arrows). Because of the deposition of drift the Ohio was forced to abandon its wide, preglacial valley and to cut a new one. (Modified after Fenneman.)

In portions of New York, Ohio (Fig. 176), Michigan, Indiana, Minnesota, and other northern states, and in Canada, the preglacial drainage has been greatly modified by glacial action. In certain areas the streams have new courses; the old valleys are so filled with drift that no evidence of them is to be obtained except by borings.

ICEBERGS

Formation of Icebergs. — On account of the muddiness of the water in front of a glacier which enters the sea (Fig. 177) and also because of the danger from the fragments of ice which continually break off from the glacier without warning, it has been impossible to determine definitely how great icebergs are formed. Ice breaking from that portion of the front of a glacier which is above the water produces small bergs, but large ones do not usually have this origin. The two figures (Figs. 178, 179) show two theories of the origin of icebergs. The first theory (Fig. 178) holds that near sea level a glacier is cut back by wave action and melting, leaving a projecting ice foot some distance beneath the surface of the water, which gradually thins toward the end. Great icebergs which suddenly appear from the water some distance from a glacier are believed by the adherents of this theory to have come from the ice foot, from which they had been broken by the buoyancy of the water. The second theory (Fig. 179) holds that the upper part of a glacier which enters the sea will project beyond the lower part, both because of the more rapid movement of the top than the bottom and because of the melting of the ice by the water. In proof of this it is stated that large masses, extending to the very top of the ice front, shear off and sink vertically into the water, disappear for a few seconds, and then reappear, almost to their original height, *before* they turn over. If the glacier projected under the water to within 300 feet of the surface, it would cause the mass to turn over at once. According to this theory most of the small bergs consist of masses broken from the ice precipices; larger ones are formed when a piece shears off and sinks into the water; and ice detached under the water may also form bergs. A third theory (Fig. 180) holds that the front of the glacier is broken off by the buoyancy of the water.

FIG. 177. — Nunatak Glacier, Alaska, entering the water of a fiord and discharging icebergs. (U. S. Geol. Surv.)

Size and Work of Icebergs. — Bergs from Greenland seldom stand 200 feet out of water, and a height of 100 feet is more usual; but icebergs have been reported from the Antarctic which are of great size, being several miles long and 500 feet or more high. Icebergs vary greatly in shape (Figs. 181, 182), those of the Antarctic regions being frequently of a tabular form, while those from Greenland are usually picturesquely irregular. If icebergs were regular in shape and without débris their thickness could be easily determined, since in the case of solid ice the part which appears above the water is only one ninth of the mass.

The principal geological effects of icebergs are two: they abrade the bottoms of the shallow seas where they strand, and they transport their load of débris until it is dropped as the ice melts. Most of the load is lost before it has been carried 100 miles, but some of the débris of Greenland icebergs is deposited on the Newfoundland Banks. It is stated that in the Baltic Sea bowlders which have been dropped from icebergs are often found upon vessels which have been sunk a few years.

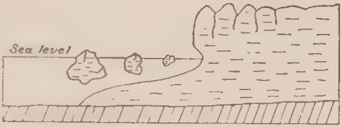


FIG. 178.

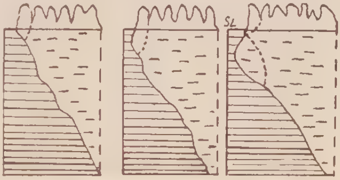


FIG. 179.

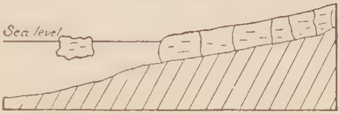


FIG. 180.

FIGS. 178–180. — Diagrams illustrating the theories of the formation of icebergs. Fig. 178. — Icebergs formed by the breaking off and floating of the foot of a glacier as the upper portion is eroded and melted back by the waves. Fig. 179. — Icebergs formed by gravity, since it is held that the upper part of a glacier will project beyond the lower part, both because of the more rapid movement of the top and because of the melting of the ice. Fig. 180. — Icebergs broken from the glacier as it enters the sea, by the buoyancy of the water.

GLACIAL MOVEMENT

There is great difference of opinion concerning the mechanics of glacial movement, and the problem may be considered as one yet to be solved.

(*1*) *Viscosity Theory.*—One of the early theories held that the motion of glaciers is due to the semiplastic or viscous nature of ice (Forbes), which permits it to move upon a slope very much as do such substances as thick tar or sealing wax, the force which urges it forward being its own weight. Experiments have been performed which appear to show that, in small masses, ice will not yield to pressure without breaking, even when the pressure is very slowly applied. If this is true under all conditions ice is not a viscous substance as has been supposed, and the theory fails.

(2) *Expansion and Contraction.* According to this theory a glacier moves downhill as a solid body, simply through alternations of temperature. When a mass suffers a rise in temperature it expands, the motion taking place in the direction of least resistance, that is, down the bed. When the temperature falls, contraction will ensue; but since gravity opposes a backward movement a gradual creeping down the bed occurs. The creep of sheet lead on a roof illustrates this action. Since ice is a poor conductor of heat, it is evident that such rapid movement as is often observed could not result from this cause.

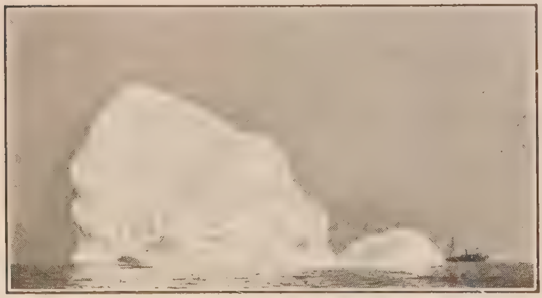


FIG. 181. — An iceberg. The vessel gives an idea of the size.

FIG. 182. — Iceberg, Labrador. The dark bands of débris were probably horizontal in the glacier. (Photo. F. B. Sayre.)

(3) *Regelation.* — A theory (Tyndall) based upon the fact that broken ice heals under pressure, even at melting temperatures, holds that the movement of glaciers is accomplished by the repeated frac-

turing and later freezing together (*regelation*) of the surfaces of the fractures when they again come into contact. Under the influence of pressure a glacier is continually yielding to fractures of all sizes, but after changing the position of its parts as a result of the downward movement of the broken fragments, it is again united by regelation. The effect of this constant rupture and regelation is thought to cause the glacier to behave *like* a plastic or viscous body. That it is not plastic is indicated by the failure of the Mer de Glace, moving at a rate of only two feet a day, to withstand a change of slope in its bed of even two degrees without fracturing.

(4) *Melting and Pressure.* — The lowering by pressure of the melting point of ice forms the basis of another theory. (Thompson.) At the points of greatest pressure in a glacier melting occurs, and the stress is relieved. The water thus formed moves to a point where there is less pressure and immediately freezes. The forward motion of the whole is, therefore, if the theory is correct, effected by a continual process of alternate melting and freezing.

(5) *Growth of Granules.* — Since the crystals or granules of glacial ice vary from one seventh of an inch or less to an inch or even four inches in diameter, it has been held that the growth of the granules of the ice is a leading factor in its movement.

(6) Other theories of an importance perhaps equal to those presented have been suggested, but none seems to explain all of the elements of the problem. Some of the difficulties have doubtless arisen from the desire to ascribe all of the phenomena of glacial motion to a single cause. The movement of glaciers will undoubtedly be found to be far from simple and to depend upon a number of factors, no one of which is alone competent to produce the characteristic movement of large bodies of ice.

Stef -dor
643-644

REFERENCES FOR GLACIERS

EXISTING MOUNTAIN GLACIERS

Folios of the U. S. Geol. Surv., in Montana, California, Washington, Oregon, and Wyoming.

ALLEN, W. C., — *Glaciers of Glacier National Park*, U. S. Dept. of the Interior.

GILBERT, G. K., — *Glaciers and Glaciation:* Harriman Alaska Expedition, Vol. 3.

RUSSELL, I. C., — *Glaciers of North America.*

RUSSELL, I. C., — *Malaspina Glacier:* Jour. Geol., Vol. 1, 1893, pp. 219–245.

SALISBURY AND ATWOOD, — *Topographic Maps:* Professional Paper, U. S. Geol. Surv. No. 60.

TARR, R. S., — *The Yakutat Bay Region, Alaska:* Professional Paper, U. S. Geol. Surv. No. 64, 1909.
TYNDALL, J., — *The Glaciers of the Alps*, 1860.

PRESENT CONTINENTAL GLACIERS

HOBBS, W. H., — *Characteristics of Existing Glaciers*, 1911.
NANSEN, F., — *The First Crossing of Greenland*, 1890.
PEARY, R. E., — *Northward over the Great Ice*, 1898.
SHACKLETON, E. H., — *The Heart of the Antarctic*, 1910.

GLACIAL EROSION

CHAMBERLIN, T. C., — *The Rock Scourings of the Great Ice Invasions:* Seventh Ann. Rept., U. S. Geol. Surv., 1885, pp. 174–248.
CHAMBERLIN AND SALISBURY, — *Geology*, Vol. 1, 1906, pp. 281–307.
DAVIS, W. M., — *Glacial Erosion in France, Switzerland, and Norway:* Proceedings Boston Soc. Nat. Hist., Vol. 29, 1900, pp. 273–322.
DAVIS, W. M., — *The Sculpture of Mountains by Glaciers:* Geographical Essays, 1909.
DAVIS, W. M., — *Die Erklärende Beschreibung der Landformen*, 1912.
GEIKIE, J., — *Earth Sculpture*, pp. 212–249.

RESULTS OF GLACIATION

CHAMBERLIN AND SALISBURY, — *Geology*, Vol. 3, 1906, pp. 327–446.
GEIKIE, J., — *The Great Ice Age.*
SALISBURY, R. D., — *Glacial Geology in New Jersey:* N. J. Geol. Surv., Vol. 5, 1902.
TARR, R. S., — *The Physical Geography of New York State*, 1902, pp. 103–154.
WRIGHT, G. F., — *The Ice Age in North America.*
WRIGHT, W. B., — *The Quaternary Ice Age*, 1914.

DRUMLINS, ESKERS, AND KAMES

ALDEN, W. C., — *Drumlins of Southeastern Wisconsin:* Bull. U. S. Geol. Surv. No. 273, 1905.
FAIRCHILD, H. L., — *Drumlins of Central Western New York:* Bull. N. Y. State Museum No. 111, 1907.
GREGORY, J. W., — *The Relation of Eskers and Kames:* Geog. Jour., Vol. 40, 1912, p. 169.

GLACIAL MOVEMENT

CHAMBERLIN AND SALISBURY, — *Geology*, Vol. 1, pp. 308–323.
OGILVIE, ALAN G., — *Some Recent Observations and Theories on the Structure and Movement of Glaciers of the Alpine Type:* Geog. Jour., Vol. 40, pp. 280–294; (especially for bibliography).
PRESTON, T., — *The Theory of Heat*, pp. 279–300; (especially for the theories of regelation, and expansion and contraction).
REID, H. F., — *Mechanics of Glaciers:* Jour. Geol., Vol. 4, 1896, pp. 912–928.

Topographic Map Sheets, U. S. Geological Survey, Illustrating Glaciers and Glacial Erosion

Mountain Glaciers

- Shasta, California.
- Chief Mountain, Montana.
- Glacier Peak, Washington.
- Cloud Peak, Wyoming.
- Mt. Stuart, Washington.
- Kintla Lakes, Montana.

Cirques and Glacial Valleys

- Chief Mountain, Montana.
- Philipsburg, Montana.
- Cloud Peak, Wyoming.
- Hayden Peak, Utah.

Topographic Map Sheets Illustrating Glacial Deposition

Drumlins

- Sun Prairie, Wisconsin.
- Boston, Massachusetts.
- Weedsport, New York.
- Waterloo, Wisconsin.
- Syracuse, New York.

Moraines

- St. Paul, Minnesota.
- Harlem and Brooklyn, New York.
- New York City and Vicinity.
- Minnetonka, Minnesota.
- Lake Geneva, Wisconsin.
- Northville, South Dakota.

Outwash Plains

- Brooklyn, New York.
- New York City and Vicinity.
- Elmira, New York.
- Whitewater, Wisconsin.

CHAPTER VI

THE OCEAN AND ITS WORK

The oceans and seas cover about 72 per cent. of the surface of the earth. The average depth of the oceans is about two and one half miles, that of the Pacific being somewhat greater than that of the Atlantic; the average height of the continents, however, is only a little more than 2000 feet. If all the dry land above sea level were washed into the sea, it would fill only one fortieth of that depression. Soundings to a depth of 32,088 feet have been made in the Pacific Ocean near Mindanao, P. I., and to a depth of nearly 28,000 feet near Japan (Tuscarora Deep). Within 70 miles of Porto Rico the ocean bottom descends to 27,366 feet, and within 10 miles of the Bermuda Islands depths of 17,460 feet are encountered. These great depths are not of wide extent, but are almost as limited as are the great heights of the continents. Moreover, the greatest depth of the oceans is practically the same as the greatest mountain height, each being about six miles. There are, however, few such excessive differences in elevation in short distances on the land as there are differences in depth in the ocean, although Mt. Everest (29,002 feet) is within 60 miles of the nearly sea level Ganges plain, and the volcano Fuji in Japan rises 12,400 feet directly from sea level.

GENERAL CHARACTER OF THE OCEAN

Topography of the Ocean Floor. — In order to gain a true conception of the topography of the ocean bottom, it must be borne in mind (1) that stream erosion, which is continually at work on the land and which tends to roughen its surface, is absent on the ocean bottom; (2) that minor depressions which may exist temporarily tend to be rapidly filled by the sediments brought to the ocean from the land and by the material carried in solution, some of which is precipitated directly and some absorbed by animals to form their shells and skeletons, only to be left upon the ocean floor after their death.

Bordering practically all of the shore lines of the oceans is a belt of water which has a depth of less than 600 feet and is from several miles to 200 miles wide. This gently sloping sea floor is known as the *continental shelf* or *submarine delta* (Fig. 183). The continental shelf is economically of great importance, since the waters lying above it are the great fishing grounds of the world. From its outer edge the sea floor slopes abruptly, so that within a few miles there are depths as great as 6000 feet, while beyond the slope is gentle but gradually increases, until within a distance of from 50 to 100 miles it attains a depth of 12,000 feet. At this depth or lower, the greater part of the ocean bottom is a great monotonous plain, so nearly flat that if the water were removed, the greater part of it would appear to the eye to be almost perfectly smooth.

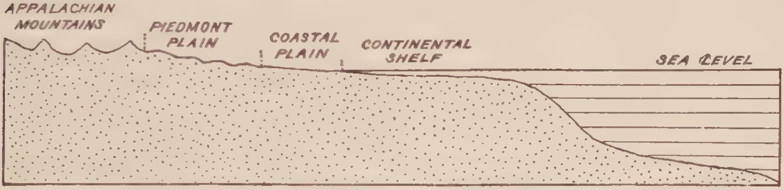


FIG. 183. — Profile showing the continental surface from the Appalachian Mountains to the deep sea.

Irregularities of the Ocean Floor. — The irregularities which exist on the ocean bottom are (1) depressions on the continental shelf which are extensions of river valleys (p. 227); (2) the steep slope at the outer edge of the continental shelf; (3) volcanic cones, built up from the depths of the sea; (4) precipices, due to faulting (some in the Mediterranean being 3000 to 5000 feet high); (5) well-defined, wavelike ridges, corresponding to mountains on the land; and (6) broad plateau areas which rise several thousand feet above the deeper portions. Such a plateau extends beneath the Atlantic Ocean from Iceland to a point in the South Atlantic almost opposite the southern extremity of Africa. It reaches the surface in Iceland, the Azores, St. Paul, Ascension, and Tristan de Cunha islands, but, for the most part, lies 6000 feet or more below the surface.

Composition of Ocean Water. — The water of the oceans contains about three and one half per cent. of mineral matter in solution, more than three fourths of which is common salt (NaCl). Of the total mineral matter in solution, the salts of sodium, magnesium, and calcium constitute 97 per cent. Almost every known element has been found by analysis to be dissolved in sea water, and they are all more or less radioactive. The relative amounts of the common salts which occur in ocean water are as follows[1]:

Common salt, $NaCl$	77.76	Potassium sulphate, K_2SO_4	2.46
Magnesium chloride, $MgCl$	10.88	Magnesium bromide, $MgBr_2$	.22
Magnesium sulphate, $MgSO_4$	4.74	Calcium carbonate, $CaCO_3$	.34
Calcium sulphate, $CaSO_4$	3.60		100.00

In a discussion of the composition of sea water not only the dissolved mineral matter should be considered, but the dissolved gases as well, since oxygen is essential for the existence of marine organisms and for oxidizing dead matter of organic origin. In addition to oxygen, nitrogen and carbon dioxide are present. In fact, the ocean probably contains from eighteen to twenty-seven times as much carbon dioxide as the atmosphere and is the great reservoir of this gas. It is not, however, equally distributed, but is more abundant in polar seas than in equatorial, since cold water absorbs much more of it than warm.

Temperature of the Ocean. — The temperature of the surface of the ocean varies with the latitude, from a mean annual temperature of 80° F. at the equator to one of 40° F. at the poles. Since the rays of the sun do not penetrate the water to great depths, it is probable that the seasonal changes are not felt below 50 feet. The temperature at the bottom of the ocean is surprisingly cold, being about 29° F. at the poles and 35° F. at the equator. This layer of cold water is very thick; for if we consider water above 40° F. as warm, the layer of warm water is nowhere more than 4800 feet thick, and is usually considerably less. The low temperature of the deep water is due to the movement of the waters from the polar regions, which slowly creep toward the equator along the ocean bottom, so that we find in the tropics, at great depths, the low temperatures which are encountered only on the surface in the Arctic and Antarctic regions. Exceptions to the rule that the temperature decreases from the surface downward are found in such seas as the Mediterranean, the Gulf of Mexico, and the Red Sea. In these seas the temperature of the bottom is approximately the same as that at the bottom of the strait separating them from the ocean, and the surface temperature is almost constant, being practically the average temperature of the surface in winter. In the Mediterranean, for example, the temperature at a depth of 6000 feet is 55° F., while in the Atlantic at

---

[1] *Data of Geochemistry*, Bull. U. S. Geol. Surv. No. 491, p. 23.

that depth it is 35° F. This difference in temperature is due to the failure of the cold waters which slowly move on the ocean bottom from the poles toward the equator, to reach the confined basin of the Mediterranean (Fig. 184).

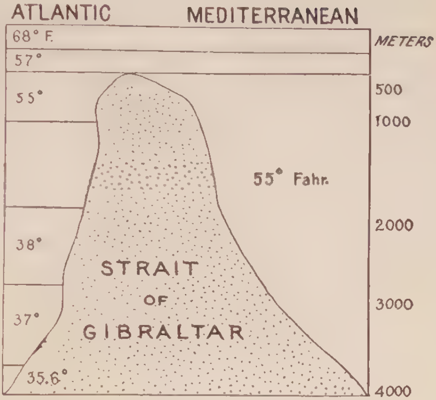


Fig. 184. — Diagram showing the peculiarity of temperature of the Mediterranean.

Distribution of Marine Life. — There is little doubt that the marine life of the past existed under conditions similar to those of the present, with the exception, perhaps, that in the early history of the world the great depths were less inhabited than now.

In the seas of to-day the greatest abundance of animal life is found in the shallow waters of the continental shelf, where food, supplied both from the sediments brought in by the streams and by the plants that grow there, is plentiful. However, some animals are able to withstand the enormous pressure of the water at great depths, although the abundance and variety is small compared with that which flourishes in the shallow waters. When the oceanic cables are raised for repairs, marine animals are often found attached to them. Warm waters are on the whole more favorable to organisms than cold, although even in the waters bordering the Antarctic Continent the fauna is often varied and plentiful. At and near the surface of the ocean microscopic and other small organisms appear in great numbers, and on the bottom numerous forms of life are frequently found, but in the thousands of feet of water which lie between the bottom and a few hundred feet of the surface of the deep seas there is an almost total absence of life. There is no portion of the land surface on which life is so nearly absent. This is in contrast with the shallow waters, where life is probably much more abundant than on any portion of the dry land. Certain species are restricted to muddy bottoms; some to sandy; some thrive best in clear, quiet waters out of reach of land sediments; while others are most abundant where the water is in motion. Plant life is limited to the depth to which light penetrates and is, consequently, scarce in bottoms lying at depths greater than 100 to 200 feet. Since the presence of ammonium carbonate in water aids marine organisms in the formation of their calcareous shells and skeletons, and since this compound is most abundant in warm waters, it is probable that when the shells of fossils are thick, the water in which they lived was warm. Thus the existence of thick-shelled, Paleozoic fossils in the rocks of the Arctic region indicates that when they were alive, the waters in that region were much warmer than now. It is evident from the above that in order to understand the life and physical conditions of the remote past a knowledge of the habits and conditions of life of animals now living is necessary.

Age of the Ocean. — Attempts have been made to estimate the age of the ocean from the quantity of salt dissolved in it. Such estimates are based on the assumption that all of the salt of the ocean has been derived from the weathering and erosion of rocks and has been carried to the seas by streams. The simplest form of the problem assumes that the age of the ocean may be determined by dividing the total amount of salt in it by the amount of this mineral carried to the sea each year by streams. The amount of salt in the ocean can be determined with considerable accuracy, since the composition of sea water varies little in different parts of the world, and the approximate total volume of the ocean is known. There are, however, a number of doubtful elements in the problem. (1) The amount of salt discharged by rivers may have varied from time to time. The rate of discharge has undoubtedly been hastened through human agency. The importance of this factor is seen in the fact that 14,500,000 metric tons of common salt are mined or extracted from salt wells yearly. If this is annually returned to the ocean, it is evident that the present rate of discharge is higher than in the past. (2) The salt blown upon the land from the ocean is considerable and must be deducted from the total carried in. (3) The salt received by the decomposition of the rocks by marine erosion (p. 202), and from volcanic ejectamenta must be subtracted. (4) Much salt once in the ocean is now stored within the sedimentary rocks.

When the known factors are considered, it is " inferred that the age of the ocean, since the earth assumed its present form, is somewhat less than 100,000,000 years."[1]

The amount of calcium carbonate in the oceans cannot be used as a basis for an estimate of their age, since some of it is precipitated upon reaching the salt water, and much of it is used by animals and plants for their skeletons and shells.

MOVEMENT OF THE WATER

Wave Motion. — Since marine erosion is accomplished chiefly by wave action, it is important to know something of the theory of wave motion, of the height and force of waves, and of the depth to which they are effective. Storm waves are set in motion as a result of the friction between the wind and water. The water *appears* to move forward, just as do the waves in a field of grain which is agitated by the wind. If a pebble is thrown into a pond on a calm day, waves

[1] Clarke, F. W., — Bull. U. S. Geol. Surv. No. 490, p. 142.

are set in motion and any floating object is seen to rise and fall as the crests and troughs of the waves pass under it, but it is not borne along. As each wave glides under the object, it is moved forward a short distance, but as soon as the crest has passed beneath it, it comes back to its former position. In storm waves, however, the friction of the wind drives some of the surface water along and thus produces surface currents (p. 217). The height of a wave is the vertical distance between the trough and the crest, and the wave length is the distance from crest to crest. The wave length in heavy storms varies but little from 600 feet, although waves more than twice that length have been observed in the southern ocean. Each particle of water in a wave moves in a vertical orbit (Fig. 185), *i.e.*, if a wave is ten feet in height the diameter of the orbit is ten feet. In open seas storm waves may be 20 to 30 feet high, and waves of 50 feet have been reported; it is, perhaps, doubtful if waves exceeding 50 feet in height are ever developed in the open ocean. Waves 10 to 15 feet high are propagated at a rate of about 60 miles an hour.

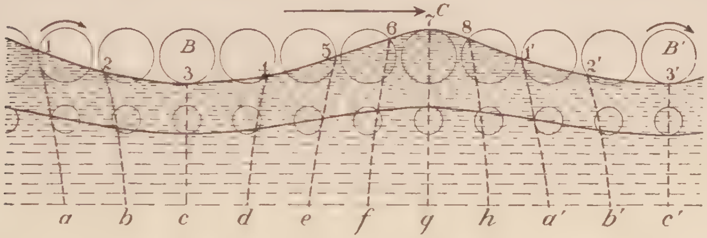


FIG. 185. — Diagram illustrating the orbital movement of water in waves. The particles of water move forward in the crests and backward in the troughs, each particle moving in a closed orbit.

Wave motion is propagated indefinitely downward, but rapidly decreases from the surface to the bottom (Fig. 185), so that at comparatively shallow depths even sand is not disturbed; the force of wave motion is one fifth at 65 feet (20 m.), one fiftieth at about 190 feet (50 m.), and perhaps not effective below 230 feet (70 m.). The depth to which agitation extends is in the ratio which the length bears to the height. Thus, a wave 30 feet long and 10 feet high would move the water 6 inches vertically at a depth of 10 feet, whereas a wave of the same height and three times the length would agitate the water 18 inches below the bottom of the wave. (Wheeler.) In violent storms it is possible that there is some motion at 3000 feet, but, in general, the mechanical action of the waves is not perceptible at depths greater than 600 feet. This last estimate is based upon the occurrence of ripple marks to be found upon the sand of the ocean bottom.

Storm waves sometimes travel great distances, even thousands of miles, preserving their length and velocity, but diminishing in height until they become gentle swells.

The Breaking of Waves. — As a wave nears a shelving shore its length is decreased and its height increased. The *breaking* of the wave is the result of friction with the bottom, which retards the lower part, while the crest, continuing with its previous speed, finds itself without support and "breaks." This tumbling crest is called a *breaker* or *roller.* Since waves of the same height break in about the same depth of water, a line of breakers is formed. If the ocean bottom descends gently, the water of the breakers rushes upon the shore, and gravity then draws it back down the beach and along the bottom beneath the incoming wave as the *undertow.* On pebbly (shingle) beaches the grinding of the pebbles as they are moved forward by the waves and carried back by the undertow can be heard, even when the waves are small.

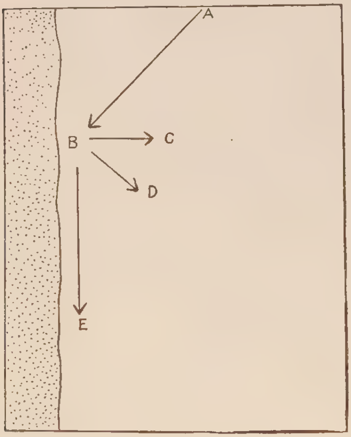


Fig. 186. — Diagram showing the directions of the various currents produced by a wave moving in the direction *AB*, a shore current *BE*, and undertow *BC*, and a reflected wave *BD.*

When waves strike a coast obliquely, a *shore current* (p. 217) is produced (Fig. 186), and on coasts where the prevailing direction of the storms is fairly constant, the importance of currents of this origin in transporting sand and gravel is very great.

Force of Storm Waves. — The force of waves varies with their height, but it is difficult to reduce the force of impact with which a breaking wave strikes a cliff to an exact mathematical calculation. Their strength is, however, influenced by the force of the wind which generates them, by the depth of the water over which they have moved, and by the distance which they have traveled. Experiments at Cherbourg, France, showed that the force of storm waves on that coast varies from about 600 to 800 pounds a square foot. The force of the impact of waves 10 feet high on certain harbor walls and piers was determined to be 1.36 tons a square foot. The average wave pressure on the coast of Scotland for the five summer months is 611 pounds a square foot and for the six winter months is 2086 pounds. At Dunbar in the North Sea the pressure is sometimes three and a half tons a square foot.

Height of Storm Waves. — On an islet off the coast of Oregon (Tillamook Rock) which is exposed to the sweep of the ocean, the waves of a storm in 1912 dashed against the lighthouse with such force and to such a height as to break the heavy glass of the lantern 132 feet above the sea. During another storm on the same islet a mass of concrete, weighing half a ton, was thrown to a point 88 feet above sea level. During the construction of the breakwater at Plymouth, England, blocks of stone weighing from 7 to 9 tons were removed from the seaward side of the breakwater at low-water level, carried over the top, a distance of 138 feet, and piled upon the inside. During a heavy gale three and three quarters million tons of shingle are estimated to have been taken from Chesil Bank, England, and carried seaward by the waves.

The height to which the water of storm waves is thrown is often very great. At Alderney breakwater, in England, the spray from the breaking waves was thrown upward to a height of 200 feet. At Hastings, England, water was thrown as high as the top of a large hotel, and pebbles were lifted from the beach and carried across the wide promenade into the bedroom windows of the houses fronting the sea. It is stated that windows in the Dunnet lighthouse, Scotland, were broken at a height of 300 feet above high-water mark, by stones swept up the cliff by sheets of sea water during heavy gales.

Tides. —Tides must be considered in a discussion of the work of the ocean, since they are an important, though usually inconspicuous agent. Tides are produced by a combination of the attraction of the sun and moon, and of the rotation of the earth; and almost every part of the ocean experiences two high and two low tides each day. Although the tide in mid-ocean is only about three feet high, its height becomes greatly increased when it approaches shallow shores or enters funnel-shaped bays or estuaries. In the Bay of Fundy, Nova Scotia, for example, the difference in height between low and high tide is sometimes greater than 50 feet. Because of its effect on the level of the water, the tide permits a wide vertical range for the work of waves on shores.

Tidal Currents. — Tidal races or currents, such as that at Hell Gate, in the City of New York, are not infrequent in narrow straits, and are often effective in erosion. The race at Hell Gate is due to the fact that the tide rises higher in Long Island Sound than in the bay of New York harbor, and to the further circumstance that the time of the high tide is different on the two sides of the strait. The inlets of barrier islands

(p. 221) and the channels (thoroughfares) back of them are kept open largely by tidal scour, and the deep waterways in some bays are sometimes maintained in the same way. The work accomplished by tidal currents consists more in the transportation of material prepared by the waves than in the actual wear of the coast.

The importance of tides to man is considerable. Many of the important harbors of the world could not be entered without tides. This is shown by the fact that ships must wait until the water is deepened by high tide before entering. The washing out of harbors by the tides twice a day is of great sanitary importance. The production of power from tides has not as yet been financially successful, but the possibility of the use of tidal power in the future in the generation of electrical energy is worthy of mention.

Tidal Bores. — When a tide enters the mouth of a river which is obstructed by the form of the entrance and by the shallows, its progress may be so retarded that its waters will, for a while, be prevented from passing up the valley. When its height finally becomes great enough, it rushes up in one or more great waves, which are called *bores*. In the Tsientang River, China, and in the Amazon River, Brazil, waves 20 or more feet in height are said to have been developed at times in this way. Smaller bores occur in other rivers. These waves are characteristic of but few rivers and are not of daily occurrence in any, but in such rivers as those cited they sometimes tear out the banks, destroy forests along the shores, and wash away islands.

Earthquake Waves. — Because of their great length, waves generated by earthquakes (p. 292) rise to great heights when they reach shelving shores. Such a wave 10 to 30, or perhaps more, feet in height struck the coast of Japan in 1896, killing 26,975 people, destroying $3,000,000 worth of property, and changing the shore line in many places. Because of their infrequency, earthquake waves are of little importance in marine erosion as compared with storm waves.

Ocean Currents. — The great currents of the ocean, such as the Gulf Stream, perform a very slight work of erosion or transportation, but are of vast importance in modifying past and present climates of those regions near which they pass. This is due to the influence of the winds, since they convey the warmth of the poleward currents and the cold of the equator-moving currents to the adjacent lands.

MARINE EROSION

Factors in Marine Erosion. — The impression one receives on seeing a wave strike a rocky shore is that the blow and the weight of the water are the only forces which are important in marine erosion. This, however, is an error. (1) When a wave is dashed against a cliff, every crack and cranny is more or less filled with water, and the hydrostatic pressure exerted tends to force the walls of the fissure apart. This force sometimes amounts to three tons on the square foot; a force which, often repeated, must accomplish an important work. (2) Moreover, the air in the fissures, even above the reach of the waves, is suddenly compressed and forced into the minute cracks as the waves dash against the cliffs. Upon the withdrawal of a wave the pressure is suddenly released, and the air and water rush out with a suction which, when frequently applied, may loosen and dislodge large blocks of rock. An often-quoted example is that of the Eddystone lighthouse, England, in which a securely fastened door was driven *outward* as a result of the partial vacuum produced by the withdrawal of a wave during a storm in 1840. Blocks of stone in well-built sea walls are sometimes started from their places, partly at least in this way. (3) The rocks which are broken or quarried from sea cliffs by the impact of the waves and in other ways become tools with which the waves are able to accomplish their greatest work of erosion. As these are lifted by the waves and hurled against the cliffs, they act as hammers which beat to fragments the rocks against which they strike. A high cliff is affected in the same way as a lower one, but is usually cut back more slowly, because as the waves undercut it, the talus (p. 29) falling from above may accumulate in quantities greater than the waves can quickly remove. Under such conditions the energy of the waves may be largely expended in grinding to pieces and removing the talus. Sea cliffs, however, weather back more rapidly than cliffs inland, as they are wet with spray and are usually undermined by springs and are comparatively free from talus. When a cliff descends precipitously into deep water the waves merely wash up and down and, having no tools with which to cut, wear it back very slowly. (4) The spray thrown up by the waves also has an erosive effect upon certain rocks, since it washes away the weaker ones and dissolves others which it can affect chemically. In this latter way silicates are broken down and limestones are dissolved.

Shore Ice. — In high latitudes shore ice protects the shore during the winter months, and even when loosened by the summer thaw it prevents the waves from breaking against the coasts with their full force. Shore ice, nevertheless, is important in the erosion of coasts in regions where it forms. During the winter a broad shelf of ice develops, whose thickness is usually much greater than that which would result from the direct freezing of the sea, which even in polar regions seldom exceeds 8 or 10 feet. The thickness of 30 to 60 feet to which this shore ice or ice foot forms is the result partly of the direct freezing of the ocean water, partly of the accumulation of snow on the ice, which is converted into ice by the water from the waves, and partly of the action of storms in heaping up the ice. Shore ice may hold a load of pebbles, both on its upper surface and near the bottom: the former falling on the ice from the cliffs, as a result of the loosening of the rocks by frost; the latter being obtained from the beach which is frozen to the bottom of the ice. Therefore so far as the position of the débris is concerned, shore ice resembles glaciers (p. 156).

During storms this ice is broken into great rafts or floes, and large masses are driven upon the shores by the force of the wind and waves, while in calmer weather they are moved backward and forward by the tides. The stones embedded in the bottom of the ice grind and crush the rocks over which they are pushed, scratching and polishing rocky shores very much as glaciers polish and scratch the rocks over which they move (p. 183). As in the case of glaciers, the rock tools which accomplish this work are themselves ground to powder (p. 159). It is probable that many of the striations on the rocks of the coast of Labrador, and even on coasts as far south as Newfoundland, were produced by floe ice and not by glaciers. The striæ made by the former, however, seldom have a uniform direction.

Ice in Lakes. — Ice has much the same effect in protecting and eroding the shores of lakes as in the seas, but the protection which it affords is probably relatively greater, because the waves are usually less effective. The absence of strong shore lines in some glacial lakes (such as those which formerly existed in New York and Massachusetts) which may have been in existence for a long time, may have been largely due to a protecting fringe of ice which prevented the waves from cutting back the shores.

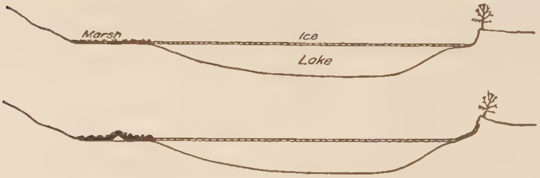


FIG. 187. — Diagrams showing the effect of ice shove in producing "walled lakes." (After Hobbs, *Earth Features*.)

If a lake freezes over completely and is repeatedly subjected to considerable changes in temperature, it may, by the expansion of the water in refreezing, produce a strong "push" on the shores. The expansion of the ice which accomplishes this result is produced as follows. Water freezes at 32° F., and in so doing expands one ninth in volume, but when the temperature of the ice becomes lower than 32° it contracts. This causes the ice to pull away from the shores or to crack. The water which rises in the cracks soon freezes, and when the temperature is again raised, the ice will expand so that the surface will be too large for the lake in an amount equal to the width of the cracks, and will either override the shores or push them up by horizontal pressure. If the shores are marshy they may be ridged or arched up into gentle folds. Such a push may make a ridge or wall about a lake if the shores are of sand and gravel. "Walled lakes" are not uncommon in Canada and in the northern United States (Fig. 187). The ridging may be increased to some extent by the ice driven up by the waves in the spring.

Results of Marine Erosion

The erosive work of the ocean is constant; in storms the waves strike with great violence, at other times more gently, but always some work is being accomplished. The conspicuous work of the waves is on the cliffs which border the sea. The rapidity with which cliffs are worn back and the sharpness of their profile depend upon a number of factors: (1) the hardness or softness of the rock, (2) the presence of cracks and joints, (3) the attitude of the beds, (4) the depth of the water, and (5) the height of the waves, the work of the waves being confined to a belt extending a little above high tide and slightly below low tide.

If the water at the base of a cliff is deep, the incoming waves do not break. Moreover, since no rock fragments are available for battering the shore, such a wall may endure many centuries with little change. On those portions of the Outer Hebrides where no gravel exists, barnacles are said to be as abundant on the wave-swept cliffs after a storm as before. Since seaweeds often flourish upon the shores where the waves are very active, they are important in protecting the rocks upon which they grow.

Effect of Erosion on Different Materials. —It is evident that soft chalk or glacial drift will be worn back much more rapidly than hard granite. At Cape de la Hève, France, where the chalk cliffs are 300 feet high, the shore is being cut back at a rate of about one yard a year, and the lighthouse stationed there has been twice set back. The annual loss of these cliffs, for a distance of 142 miles, is estimated to be about five and one half million cubic yards. (Wheeler.) So effective is the marine erosion of some chalk cliffs that some of the streams flowing over them are unable to deepen their beds with sufficient rapidity to

FIG. 188. — Chalk cliffs on the coast of France. The waves have cut back the cliffs so rapidly that the streams enter the sea from hanging valleys.

keep pace with the wearing back of the cliffs and consequently fall over them from hanging valleys (Fig. 188). The wear on granite cliffs, on the other hand, is often so slight that the battering of the waves for a century is scarcely perceptible. Along the coast of Marblehead, Massachusetts, granite, well within reach of the waves, still bears glacial striæ, showing that thousands of years of wave wear have not been effective on this hard rock. Since low-lying, sandy shores are apt to lie in places where sand is accumulating, they usually suffer less than rocky and precipitous shores. On such a coast, however, a slight change in the currents such as that due to unusual or prolonged storms may cause the shores to be cut away rapidly, as has been true of Coney Island, New York, and along the New Jersey coast, where the former sites of houses and hotels are now covered by the sea.

FIG. 189. — Undercutting of massive granite by wave action.

Influence of Joints and Other Planes on Erosion. — The profile of a cliff is largely determined by the nature and trend of the divisional planes of the rock of which it is composed (Fig. 189), especially of the stratification planes and joints.

If stratified rock is not strongly jointed and dips toward the sea (Fig. 190 *A*), the cliff formed will incline in the same direction. In such a case the wave moves up the slope with little resistance, since an overhanging cliff is absent. When the strata dip gently towards the sea and a porous stratum rests on an impervious one, landslides may occur, when the porous stratum is undermined. If the strata are inclined towards the land (Fig. 191 *A*) overhanging cliffs will be formed, since as one layer is worn back another equally overhanging, is exposed. It is on such cliffs that the waves are most effective. If the strata are horizontal the base of the cliff is excavated, but as the upper part is in the form of a stair (Fig. 192 *A*), the waves have little effect. It should be borne in mind in this connection that if the joints of the rock are better developed than the stratification planes, the profile of the cliff will depend largely upon their direction, so that

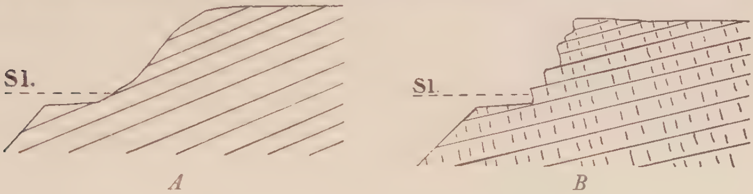


FIG. 190. — *A*, cliff formed in seaward-dipping strata without strong joints. *B*, cliff formed in strongly jointed seaward-dipping strata.

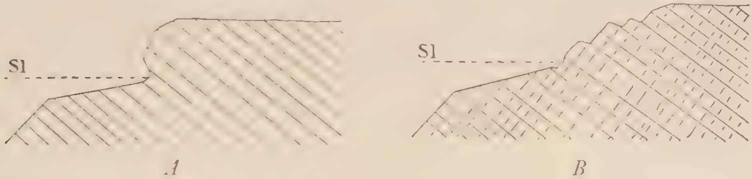


FIG. 191. — *A*, cliff formed in landward-dipping strata without strong joints. *B*, cliff formed in strongly jointed, landward-dipping strata.

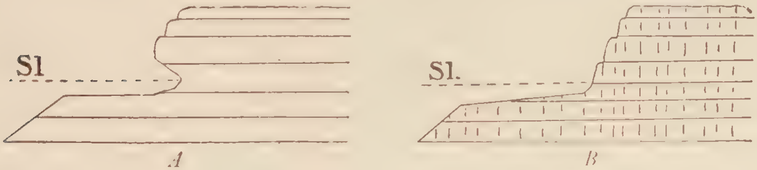


FIG. 192. — *A*, profile of a cliff formed in horizontal strata without strong joints. *B*, profile of a cliff formed in strata with strong joints.

FIGS. 190–192. — Diagrams showing the profiles of cliffs formed by wave erosion.

an overhanging cliff (Figs. 190 *B*, 193) will be the result of joints inclining inland; a sloping cliff, of joints that incline toward the sea (Fig. 191 *B*); and a vertical cliff, of vertical joints (Fig. 192 *B*).

In overhanging cliffs the dismemberment sometimes begins at the top of the cliff, where the agents are not the waves, but the rain, frost, etc. In such cases the work of the sea consists largely in keeping the base of the cliff free from talus. The height of a sea cliff depends, to some extent, upon the rapidity of marine erosion, since if weathering is more rapid than the work of the ocean, talus will accumulate at its base and protect the shore. In this connection the importance of springs and seepage from underground water should not be overlooked, for they often assist in undermining cliffs. Loose material, such as sand or glacial deposits, will not form cliffs unless the erosion is very rapid.

FIG. 193. — The effect of marine erosion on strongly jointed beds. Nantasket Beach, Massachusetts. (Photo. S. Powers.)

Coves and Headlands. — The irregularities which result from marine erosion may in general be classed as headlands and crescent-shaped beaches called coves, and are brought about (1) by the unequal resistance of the rock, the weaker being cut away more rapidly than the stronger. Such a condition results when vertical or steeply dipping strata, composed of strong and weak beds, lie at right, or at considerable angles to the coast (Fig. 194), and a similar shore line is produced when a rock is much more jointed or fractured in one portion than in another. (2) Where the force of the waves is greater on certain parts of shores than on others,

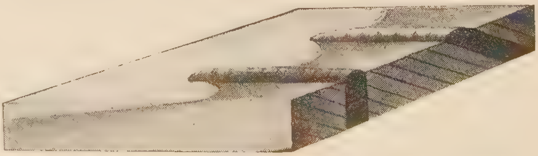


FIG. 194. — Block diagram showing coves formed in weak strata, a stronger stratum and a dike (page 324) projecting as headlands.

coves and headlands may also result. Coves are not cut back indefinitely, since after a time the headlands protect them from the full force of the waves and equilibrium is established. When this condition is attained, the headlands and coves are worn back at an equal rate. It is evident from the above that wave action is able to develop small irregularities of coast line, but not great ones.

Sea Caves and Blowholes. — Caves (Fig. 195) are often developed on rocky shores where the rock is strong enough to form a roof. If the rock is weak, chasms develop. Such chasms or gullies sometimes extend across narrow headlands, converting the outermost parts into islands. Caves occur at the bases of cliffs and are formed in one of several ways, or by a combination of them: (1) by the beating of the waves, especially if the water near the shore is neither too deep nor too shallow and if there is a supply of débris which can be used in the work of excavation; (2) by quarrying along joints. (3) Since the level of underground water near the coast is sea level, solution caves are not uncommon at bases of cliffs in limestone strata. Such caves are often enlarged by the waves. (4) If a weak bed of horizontal rock is at sea level and is subjected to the attack of the waves, it affords especially favorable conditions for excavation by waves. In the development of caves hydrostatic pressure and the compression and expansion of the air are important forces. Fingal's Cave has been thus quarried out of the lava of the south shore of the island of Staffa. It extends inland 200 feet, the floor being below

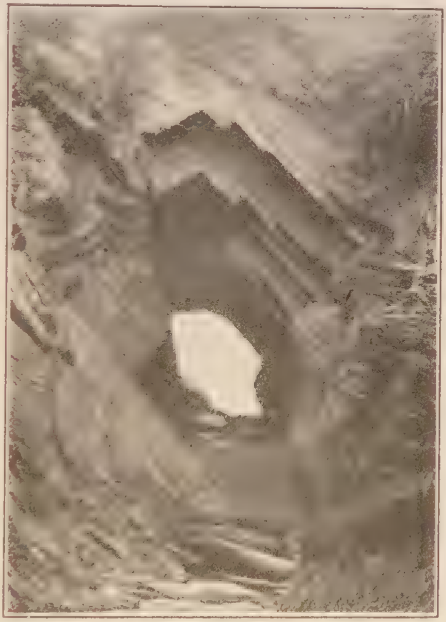


Fig. 195. — Sea cave, Watermouth, England

The sea worked along some fault or plane of weakness in the slate. The enlargement of the cave was assisted by the cleavage planes. (E. A. N. Arber, *The Coast Scenery of North Devon.*)

Fig. 196. — Percé Rock, Gaspé, Canada. (Photo. S. Powers.)

sea level and the roof more than 50 feet above. Sea caves are excellent indicators of ancient sea levels (p. 214).

Sea caves occasionally extend inland and open to the surface of the ground, sometimes behind headlands one hundred or more feet in height, and at considerable distances from the shore. During quiet weather these openings appear on the surface as deep wells, but during storms the water is sent through them with great force, sometimes throwing spray high into the air, and they are consequently known as *blowholes, spouting horns*, etc. Blowholes are sometimes formed simply by the landward extension of sea caves whose bottoms, as well as roofs, usually have a strong upward inclination inland. They are also formed when, in the landward cutting of a cave, a vertical joint is encountered which, when enlarged by hydrostatic pressure and the compression and expansion of air, is drilled to the surface.

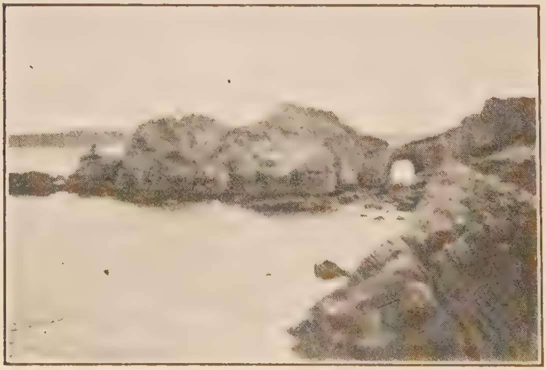


Fig. 197. — A sea arch. When the roof falls the point will become an island. (De Martonne.)

Arches are not uncommon features on some coasts. They are formed (1) by the uniting of two caves on opposite sides of a head-land, as is illustrated by Percé Rock in Quebec (Figs. 196, 197), or (2) by the partial collapse of the roof of a cave.


Fig. 198. — Stacks, Skye, Scotland.

Stacks. — Waves sometimes quarry along strong joints, leaving isolated portions of cliffs in the form of chimneys or *stacks* (Fig. 198). Stacks are also formed by the falling in of the top of a sea arch (Fig. 199). High stacks and chimneys are most common in horizontal or gently inclined beds, where the strike (p. 253) coincides with the general trend of the coast. The Old Man of Hoy on the coast of the Orkney Islands is a well-known example. This is an angular column of red and yellow sandstone, more than 600 feet high. Many examples of such structures are to be seen on the rocky shores of New England and Nova Scotia, in the Bermuda Islands, and on the shores of Lake Superior. If the rock is resistant, the stacks withstand the battering of the sea for many years, and as the sea cliffs retreat, may be left behind as rocky islets.

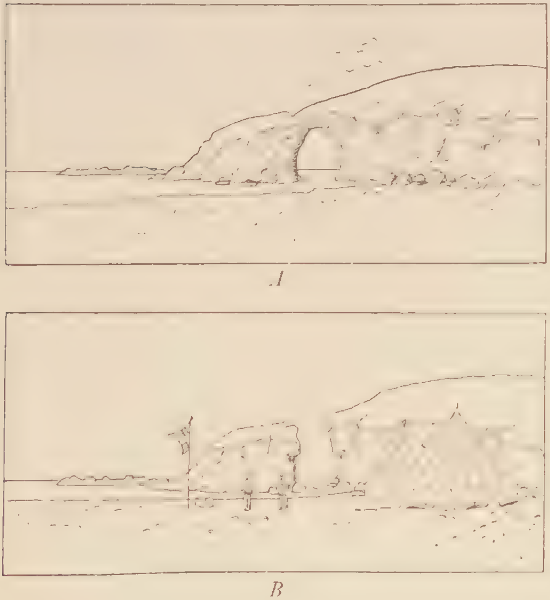


Fig. 199. — The Burgermeister Gate: *A* in 1864, and *B* in 1899 after the arch had fallen leaving a stack. (Drawing after Andersson.)

Marine Terraces. — As waves cut back a shore, they develop a submarine terrace (Fig. 200) which extends from the base of the cliffs and slopes gently seaward until

FIG. 200. — Plain of marine denudation, Yorkshire, England. (Photo. J. W. Gregory.)

it ends abruptly in deep water. The width of such a terrace depends upon the distance that the waves have cut into the land — the *wave-cut terrace* — and the distance to which the terrace has been built out by the material worn from the cliff and carried out to the edge of the rock terrace by the undertow — the *wave-built terrace* (Fig. 201). The depth of the water over the outer edge of the "cut and built" terrace depends upon the size of the waves which prevailingly beat against the shore. In small lakes it is slight, while in larger lakes it may be twenty or more feet in depth. The floor of the North Sea between Great Britain and Europe and of the Atlantic a few miles west of Ireland is believed by some geologists to be a plain of marine denudation. In eastern Patagonia, southern Australia, and other places the sea beats against cliffs from 200 to 1000 feet high, a fact which implies that marine erosion has cut them back tens or perhaps scores of miles.

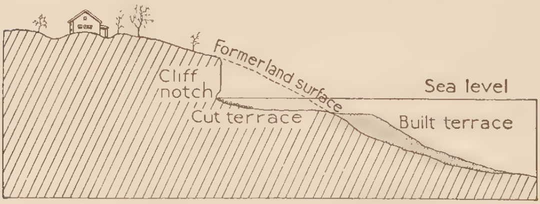


FIG. 201. — Section showing a wave-cut terrace, and a wave-built terrace, the whole constituting a wave cut and built terrace. (Va. Geol. Surv.)

FIG. 202. — Map showing how rapidly the island of Helgoland has been destroyed by the sea. The length of the shore line at different times is given. This island was used by Germany as a naval base, and its shores are artificially protected. (After Hobbs.)

Striking Examples of Marine Erosion. — The almost complete destruction by the sea of the village of Dunwich, England, within historic times, affords an excellent example of rapid marine erosion under favorable conditions. The village was built upon sand and gravel which formed at the shore a cliff 50 feet high. In the time of Henry II the village is described as "of good note and abounding with much riches," but in Queen Elizabeth's time it was reduced to one fourth of its former size. Records show that "at one time a monastery, at another several churches, then the old port, then four hundred houses at once, and gradually the jail, the town hall, the high roads, and even the ancient cemeteries, the coffins of which were for some time exposed in the cliff, were all swept away by the devouring sea." The erosion of the cliff has now ceased, as it is protected by a bank of shingle.

FIG. 203. — Map of Sharp's Island, Chesapeake Bay. In 1848 it contained 438 acres and supported a summer resort and a number of people throughout the year; in 1900 (lines) the area was 91 acres, and in 1910 (solid black) 54 acres. If the rate of erosion continues, the island will disappear before 1930. (U. S. Geol. Surv.)

The port of Ravenspur, England, where Henry Bolingbroke landed in 1399 to depose Richard II, has entirely disappeared, and no one knows exactly where it stood. Portions of the English coast, where the cliffs are from 200 to 250 feet high, have receded at an annual rate of 14 feet.

In 1831 a volcanic island — called Graham's Island — composed of volcanic ash, appeared above the Mediterranean Sea near Sicily. After reaching a height of 200 feet above the sea and a diameter of a mile, the volcano became extinct, and so rapidly and thoroughly have the waves worn it down, that not even a shoal remains to indicate its former position.

On Cape Charles, Virginia, it has been necessary to build three successive lighthouses on account of the encroachment of the sea. The first was built in 1827, 700 feet from the shore line of that time; this was abandoned in 1863, and the whole site has now been washed into the sea.

The second was built in 1864, also about 700 feet from the shore, but this now stands on the edge of the water and has been abandoned for a new tower still further inland.

A remarkable case of marine erosion is exemplified in an island in the North Sea, Helgoland, whose circumference has been reduced from 120 miles in the ninth century to 45 in the fourteenth, 8 miles in the seventeenth, and to an islet only 3 miles in circumference at present. The remnant has probably survived because of its greater height (170 feet) and because of the somewhat more resistant character of the rock (Figs. 202, 203).

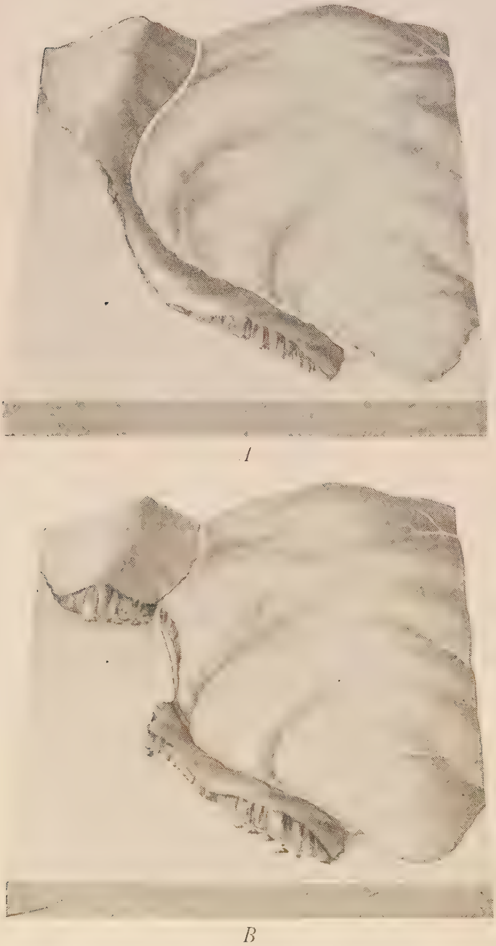


Fig. 204 *A*, *B*. — Block diagrams showing how a stream may be captured by marine erosion.

Sea-captured Streams. — When streams on approaching the seashore turn and run parallel to it for some distance before entering it, they are sometimes cut in two as a result of the more rapid erosion of the coast at some one point (Fig. 204 *A*, *B*). Streams which have been recently affected in this way enter the sea over falls.

Raised Beaches. — Shores that have been raised (Fig. 205) are sometimes marked by sea cliffs, beaches (Fig. 206), sand spits, and bars, unless the elevation took place so long ago that stream erosion and the weather have destroyed these. On the coast of Scotland the beaches rise one above another to a height of 100 feet, and the old sea caves are sometimes used as stables. The raised beaches of Norway and Scotland are occupied by villages, and without them the shores would often be deserted. On the coast of

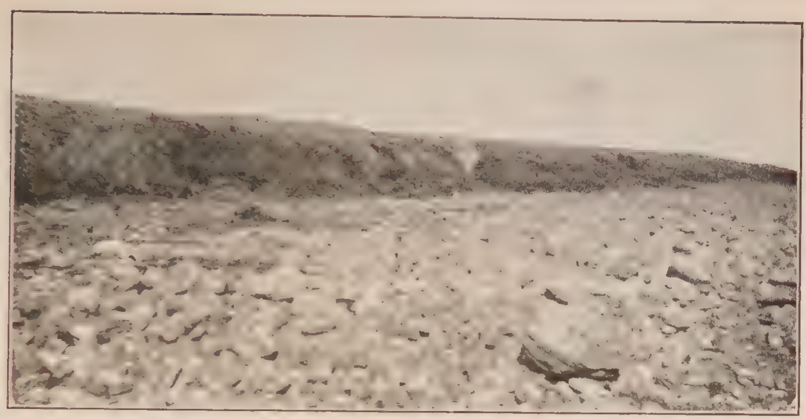


FIG. 205. — A raised beach showing the coarse bowlders of the old beach and the ancient sea cliff. (Photo. F. B. Sayre.)

California well-marked marine terraces are found 1500 feet above sea level. On the coasts of South America and elsewhere the recent elevation of the land is also proved by their presence.

Ancient Plains of Marine Denudation.— In Labrador and California ancient marine terraces are well marked. The ancient plain of marine denudation on the east coast of India is an unusually fine example of such a plain which has resulted from the long-continued action of the waves. The two striking features (Fig. 207) of the plain are (1) the evenness of the surface and (2) the steep-sided hills, the former islands, which rise above it. As the ancient shore is approached, the outliers (p. 106) (ancient islands) are more numerous; those which are near the old shore are tied to it by old sand and pebble bars. Moreover, sea caves (Fig. 208) are not uncommon in the ancient sea cliffs. Seaward of the marine plain is the coastal plain in which cuestas (p. 225) have been developed.

FIG. 206. — A plain of marine erosion with ancient islands, east coast of India. (Photo. S. W. Cushing.)

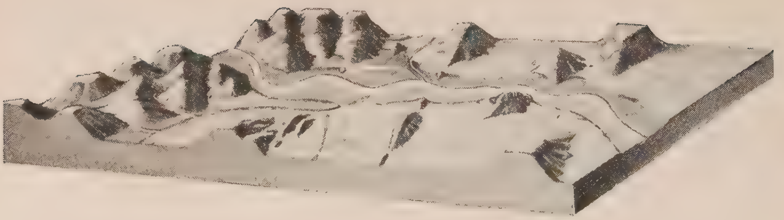


Fig. 207. — An ancient plain of marine denudation, with the former islands standing above the plain as hills, is shown in the diagram. The accordant level of the hills indicates an ancient peneplain. (Modified after S. W. Cushing.)

The New England Marine Plain. — As has been seen (p. 215), the presence of cliffs at the shore line shows that locally marine erosion may become more effective than subaërial (the work of weather, wind, and streams). The sea, however, can work only against the shore, while the effect of stream erosion and of the weather is to reduce the whole surface of the land (p. 114). The work of the sea, though powerful, is limited to the shore line, and plains produced by marine erosion are of small extent compared with the extensive plains carved by the subaërial agencies. It has been suggested, however, that at certain times, planation by the sea may become more effective than usual over much broader areas. After a region has been worn down to such an extent that the soft beds of rock are reduced to base level, leaving the harder as hills, subaërial erosion works very slowly, and the amount of sediment carried to the sea by the streams is so small that the littoral currents expend little energy in moving it. Under such conditions the surface of the land is lowered very slowly, while marine erosion is relatively much more effective. If such a stage is combined with some submergence the sea has an added advantage, and its action is concentrated on the residual hills and uplands remaining from subaërial erosion. The land bordering the Atlantic coast of North America is thought by some to have been under conditions such as these during a long period of time (Cretaceous and Tertiary).[1] The uplands of New England and New Jersey and the resistant ridges of the Appa-

Fig. 208. — An ancient shore line. The rim of the cave is 65 feet high. East coast of India. (Photo. S. W. Cushing.)

---

[1] Barrell, J., — Bull. Geol. Soc. Am., Vol. 24, No. 4, 1913, pp. 688–696.

lachian Mountains presented an irregular front to the sea, upon which marine erosion was concentrated. As a result, a plain of marine denudation many miles wide was cut. Upon subsequent oscillatory elevation, with many halts, lower plains were cut. Consequently, in traveling from western Massachusetts to Long Island Sound, instead of a much-dissected, gently sloping peneplain, one finds first the high, rugged mountains which were not attacked by the sea; then a deeply dissected, slightly sloping high plain, now almost completely destroyed; and, successively, lower plains, better preserved, until the sea is reached. The highest plain if restored would reach an elevation of from 2300 to 2400 feet in western Massachusetts; and a total of seven originally well-developed plains may be recognized, the lowest at a height of 700 feet. Below this are four plains of fainter development. If this theory is correct, the so-called New England peneplain (p. 114) is really a combination of several surfaces of marine denudation (Fig. 209).

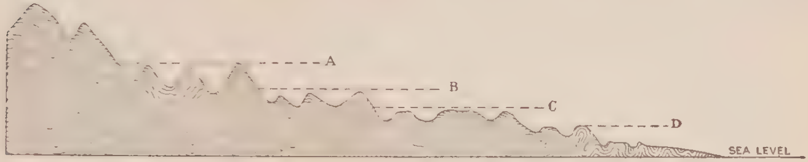


FIG. 209. — New England plains of marine denudation, according to Barrell. The dotted lines *A*, *B*, *C*, *D* are the successive levels of the sea.

TRANSPORTATION

Littoral or Shore Currents. — The sediment carried into the ocean by streams, as well as that eroded from the shores by waves, is usually soon carried away by currents produced by waves, wind, and tides. When a wave strikes a shore at right angles to its trend, the water thrown upon the shore returns as the undertow (p. 200) and may carry the sediment to great depths. The débris at the foot of the cliffs is, however, not immediately transported to the deep water, but is moved back and forth by the waves and the undertow, and is thus ground finer and finer with time. Since the velocity of the undertow rapidly decreases with the depth of the water, only the finer sand can be carried a considerable distance. Consequently, one usually finds coarse pebbles (shingle) near shore, and progressively finer sediment farther out.

When a wave strikes a shore obliquely, a portion of the water returns immediately as undertow (Fig. 186, p. 200), and a portion moves along the shore and forms a *littoral* or *shore current.* The zone of breaking waves is the road of shore drift, and it often happens that it is the waves produced by storms rather than those of the prevailing winds which determine the direction of the greatest shore drift. Large particles are not carried far by the shore currents, but the finer sand may be transported many hundreds of miles.

Tidal Currents. — Tidal currents are often of great importance in the removal of sediment (p. 221). When the tide flows through narrow passages, as between islands, or in V-shaped bays, swift currents are developed which erode and carry away the mud, sand, and gravel which come within their reach. Some tidal currents run so strongly that divers are unable to stand against them. The outgoing tide has greater power than the inflowing, since the latter moving in as a great wave fills the bays above their normal level and backs up the water of the rivers, often for long distances. On account of this accumulation of water an outflowing current begins along the bottom before the tide is wholly in, and when the tide changes this adds to the strong current which has already begun. Such strong, outflowing currents tend to keep the channels deep and open, and carry the mud and sand into deeper water.

The transporting and erosive powers of the outgoing and incoming tides are, however, sometimes almost equally strong, as was shown by an examination of a steamer which was sunk off the mouth of the Gironde River in France. The vessel rested on her keel in 36 feet of water. At the end of the ebb tide the sands were so scoured as to leave the hull supported only in the middle, but at the end of the flood tide the vessel was again completely covered, the sand beds extending 100 yards fore and aft of the vessel and 50 yards from each side. (Partiot.)

Tides not only scour out channels but may also cause the deposition of the sediment which the rivers are carrying to the sea. It often happens that sand flats are formed at the entrances of bays. If a point projects on the side of the river mouth first reached by the incoming tide, the tidal flow may carry the sediment far beyond the mouth of the river; but if no such point exists, the entrance may become more or less choked.

Features Resulting from Transportation

Beaches. — When the sea has cut a rock terrace so wide that a strip of sand and gravel is left between the cliff and the sea, a beach is formed. Along coasts exposed to strong waves the breadth of the wave-cut terrace must be much wider before sand is left on it to form a beach than in quiet water, since in the former the sand and gravel may be swept away as fast as formed even when the terrace is several hundred feet wide. Wide beaches are usually first formed within slight recesses of the coast, where the littoral currents deposit their load. Such beaches are crescent-shaped. Near the base of a sea cliff bowlders or coarse gravel will be found, but as one goes from the cliff the material of the beach is seen to become pebbly and finally to consist of fine sand. The horizontal distance over which a pebble travels before it is ground to sand is very short.

FIG. 210. — A bayhead beach. Conception Bay, Newfoundland. (U. S. Geol. Surv.)

Bayhead Beaches. — The detritus worn by the waves from the cliffs and from the bottom where the water is shallow, and that brought to the sea by streams is in part carried into deep water, where it is immediately deposited and, in part, is swept along the beach by shore or littoral currents. As the waste

FIG. 211. — Lagoon inclosed by a storm ridge. (Photo. De Martonne.)

is carried along it does not conform closely to the shore unless the indentations are comparatively slight. When it is swept into a shallow, sheltered bay or cove, it may form a *bayhead beach* (Fig. 210). When such a beach is attacked by storm waves a ridge is sometimes thrown up on the seaward edge, forming a dam behind which a shallow lake or marsh is formed (Fig. 211). An interesting fact in connection with these pebble beaches is that sometimes during a single gale an entire ridge may be moved as much as 30 feet.

Bars and Spits. — When littoral drift reaches an abrupt bend in a shore, as, for example, at the entrance of a bay which extends some distance inland, it does not follow the bend, but usually continues in the direction in which it has been moving. It therefore passes from shallow water to deep, where it drops its load. Since the portion of the littoral current that carries the sand is usually narrow, the material dropped into the deep water is gradually built up in the form of an embankment, like a railroad fill, which may, in time, extend entirely across the bay. Currents do not build bars above the level of the water, but waves may do so by washing the sand and gravel from the slopes of the bar to the top. As soon as a portion of the sand is exposed above the water, it may be blown into dunes by the wind. Since dune topography is rough, such sandy stretches often have an uneven surface.

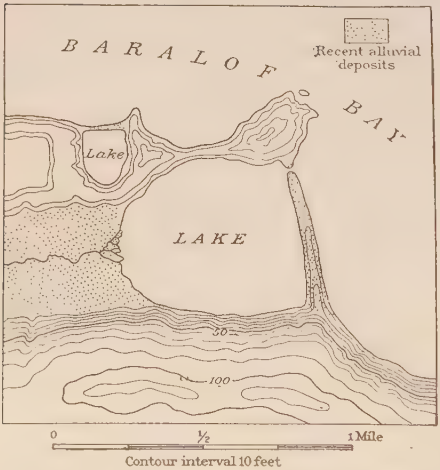


FIG. 212. — Map showing an incomplete bar almost shutting the larger lake from the sea, and a complete bar across the smaller lake. Delta filling is well shown. (Atwood.)

Often a bar is never completed (Fig. 212), since the rivers flowing into the bays have sufficient volume and current to keep a channel open. The scouring action of tidal currents may also be able to remove sediment to deep water as rapidly as it is brought in by the shore currents. Incomplete bars, when built above the surface of the water by waves, are called *spits*, and when curved by the force of the tidal current at right angles to the drift are called *hooks*

(Fig. 213). Sometimes the end of a hook is curved so far around as to form a *loop*. Provincetown harbor, Massachusetts, is an example.

Bars are often of great disadvantage to navigation, since they so shallow the water that vessels are compelled to wait until high tide before they can pass over them. In other cases constant dredging, maintained at great expense, is necessary to keep a channel open. Spits and hooks sometimes serve as breakwaters and are of considerable value to shipping in time of storm.

FIG. 213. — Hook Bay near the north entrance to Chignik Bay, Alaska. The hook was formed by shore currents. (Atwood, U. S. Geol. Surv.)

The effect of the formation of bayhead beaches and of bars by the shore currents is to shorten the coast line and give it a smoother outline.

Sand Reefs or Barrier Beaches. — When the water offshore is shallow, the waves drag bottom and build up a ridge of sand or gravel some distance from the shore, which is as high as the storm waves can lift the material. After the surface is reached the height is further increased through the piling up of sand dunes by the wind. *Sand reefs* or *barrier beaches* (Fig. 214 *A*, *B*) are therefore formed on shelving shores, along a line to which material is brought seaward by the undertow and landward by the drag of the waves. Such sand reefs are separated from the mainland by narrow lagoons, or if they have been in existence for a long time by marshes (p. 223). Sand reefs are approximately parallel to the low shores which they border. They are seldom continuous for many miles (Fig. 215), but are broken by "inlets" which are kept open by tidal scour or by water which is brought into the lagoons by the streams, or by a combination of the two. Inlets occur at intervals of from two to twenty miles on the Atlantic coast of the United States. After a sand reef is formed, it sometimes happens that a second reef is built up in front of it, leaving

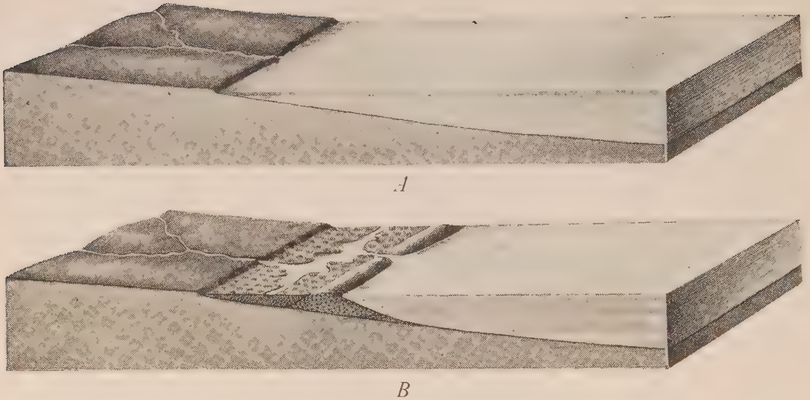


Fig. 214. — Formation of barrier islands or sand reefs. These are built near the line of breakers, off shallow, sandy shores. The lagoon in 214 *B* is shown to be nearly filled with sediment and organic matter.

a lagoon between it and the first reef. One of the most remarkable barrier beaches is off the coast of Texas and extends without a break for a hundred miles.

On the Atlantic coast of North America, from New Jersey south, the barrier beaches are so well-developed that it has been proposed to make a protected waterway by deepening the lagoons back of them. If this is accomplished, vessels will be able to sail from New York to Florida, practically free from storm waves, being protected almost the entire distance by sand reefs. The barrier beaches off the coast of New Jersey are especially favored as pleasure resorts because of their mild temperature in winter and cooling breezes in summer. In some places the barriers are growing and in others they are being washed away. Whether they grow or waste depends upon

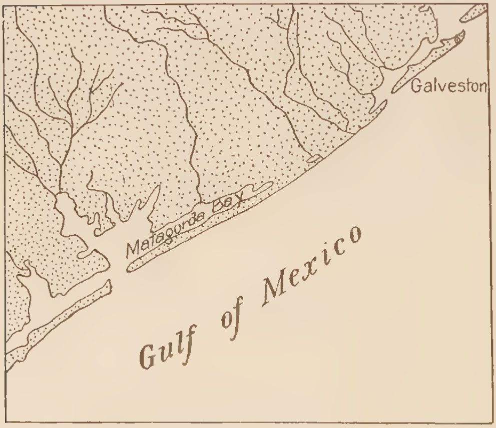


Fig. 215. — Barrier beaches on the coast of Texas. Matagorda Bay has been formed by a barrier beach, and Galveston is situated on one.

whether or not the supply of sand is too great for the waves to remove.

The lagoons back of sand reefs are gradually filled by the sediment carried in by streams from the mainland, by the sand blown in by the winds, and by the accumulation of marsh vegetation. Back of the sand reef on which Atlantic City, New Jersey, is situated, peat has accumulated to a depth of one or more feet over a wide extent. In time a marsh-filled lagoon will become dry land, and the sand reef will be joined to the mainland.

Sand reefs are sometimes hardened by the deposition of lime carbonate between the sand grains until they form rock reefs. A notable case of this kind occurs off the coast of Brazil.

Tied Islands. — Islands are sometimes tied to the mainland by sand and gravel brought by littoral currents. This is accomplished in one of two ways. (1) If littoral currents exist which move parallel to the shore in opposite directions, sometimes simultaneously and sometimes successively so that they carry material to the same point, which is generally a strait separating an island from the mainland, a tongue of land consisting of sand and gravel may unite the island to the mainland. (2) Islands are also tied to the mainland (Fig. 216) by the extension of sand spits from either the mainland or the island or from both. Many examples of islands tied to the mainland in one of these ways might be cited. Gibraltar, an island tied to Spain by a narrow sand beach called the "neutral ground," and Nahant, off the coast of Massachusetts, are familiar examples.

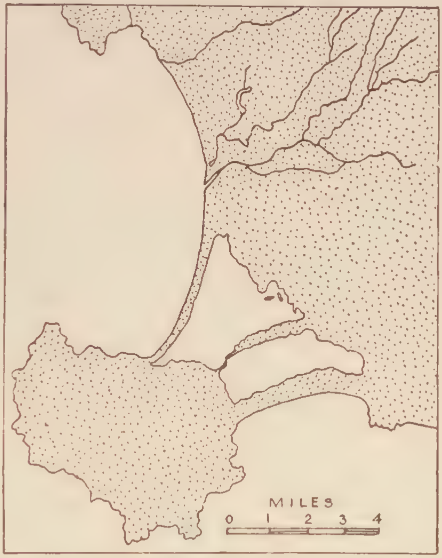


Fig. 216. — Tied island, southern Italy.

Examples of the Constructive Work of the Sea. — The work of the sea, as we have seen, is constructive as well as destructive. It is stated that on one portion of the coast of England (the estuary of the Humber) about 290 square miles have been added to the coast, while on another (Fens of Lincolnshire), the area of the land has been increased more than 1000 square miles. It is stated that for every square mile washed away from portions of this coast, three square miles have been added on others. Moreover the sea-built land is, on the whole, richer than that which was destroyed. A telegraph pole erected at a point on the English coast in 1873 was 300 feet inland in 1902. At Atlantic City, New Jersey, portions of the sand reefs are being built out while others are retreating. Hotels have had to be moved forward so as to be kept near the sea. The history of the town of Rye, England, is instructive as showing that the land may be attacked by the sea at one time and later be increased at the same point and by the same agent. This town was once destroyed by the sea, but the site is now two miles inland.

Shores

The shores of the oceans may, in general, be classed topographically as smooth or rough, or according to origin as those resulting from elevation or from submergence. To understand the configuration of a shore one must keep in mind (1) that the effect of deposition on the ocean bottoms is to smooth out all inequalities and to produce a monotonous plain which slopes gently from the beach to the edge of the continental shelf, and (2) that the effect of erosion on high land is first to roughen it.

Smooth Shores. — When a sea bottom on which sediment has long been accumulating is raised to form land, a smooth, approximately flat plain will be exposed. The low, level plain of Yucatan, which slopes beneath the water so gently that vessels cannot approach in safety nearer than three miles from the coast, so that all freight must be taken to land in shallow boats, is a good example. The land bordering the Atlantic and Gulf coasts of the United States south of New York is a somewhat broken, level plain, through which streams flow sluggishly to the sea. The underlying strata dip gently towards the sea and are composed of unconsolidated sands and clays containing marine shells. This plain varies in width from a fraction of a mile to 500 miles, extending from the Fall Line on the west to the shore on the east.

The Fall Line marks the boundary between the new, unconsolidated sands and clays of the Coastal Plain and the harder, ancient rocks of the Piedmont Plateau (p. 91). The name indicates that the streams flow over falls or rapids where they pass from the hard rocks of the old land to the easily eroded sediments of the Coastal Plain.

The greatest coastal plain in the world forms the north and west parts of Siberia and has a maximum width of more than 1000 miles. The plain is low and poorly drained.

If England, eastern Europe, and the intervening sea floors were raised 300 feet, England would be united to the mainland, the Baltic would be changed to a chain of lakes, and the North Sea would be reduced to a gulf. If this should happen, the ancient shores could be readily determined by the elevated sea cliffs, sea beaches, wave-cut terraces, and sand spits; while the raised sea bottoms would constitute coastal plains. The new shores would be smooth with few indentations.

Cuestas. — The material of land newly raised from the sea has a dip seaward, due both to the original inclination of the sediments and also to that which was brought about during the process of uplift. If the beds of recently raised coastal plains differ somewhat in resistance, the streams will in time give a zonal character to the topography, the harder beds standing higher than the softer ones. There will thus result

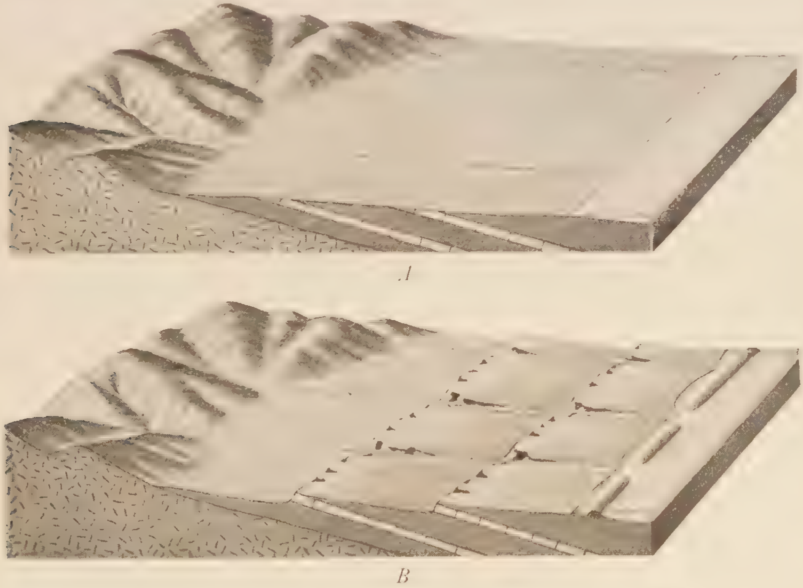


Fig. 217. — Diagrams *A* and *B* illustrate the development of cuestas. As the weak stratum of the coastal plain was cut away more rapidly than the firm, the latter formed rather steep slopes facing inward, and long, gentle slopes towards the coast.

alternating bands of lowland and highland, the lowland being bordered on the seaward side by infacing cliffs formed by the harder beds. The low ridges thus developed have a steep descent on one side and a gentle slope on the other and are called *cuestas*.

Examples of coastal plains with this banded arrangement are not uncommon. In Alabama the Appalachian Mountains are bordered by the " Black Prairie," a belt of lowland formed in easily eroded limestone. Next to this is a ridge (cuesta) which ascends rather abruptly 200 feet above the lowland, composed of more resistant limestone (Fig. 217 *A*, *B*). The geological structure of the Ghats in India (Fig. 207 p. 216) shows the formation and characteristics of such topography. Very ancient coastal plains with resulting cuestas constitute a large part of New York, Ohio, and other states.

Rough Shores. — By marine erosion a shore may be slightly roughened, but it is not possible for waves unaided to make irregular shores like those of the coast of Maine, Nova Scotia, Washington, northern Europe, British Columbia, and the coast of the Adriatic. Such shores are formed by the sinking of the land or the raising of the sea level. When a region is partially submerged the higher hills become islands or peninsulas, and the valleys become estuaries or bays. Consequently, rugged coasts bordered by high, rocky islands (Fig. 218), are evidences of subsidence. An interesting example is to be found in northeastern North America, where the coast line between New Brunswick and Portland, Maine, is 2000 miles long, although a straight line between the points is only 200 miles in length.

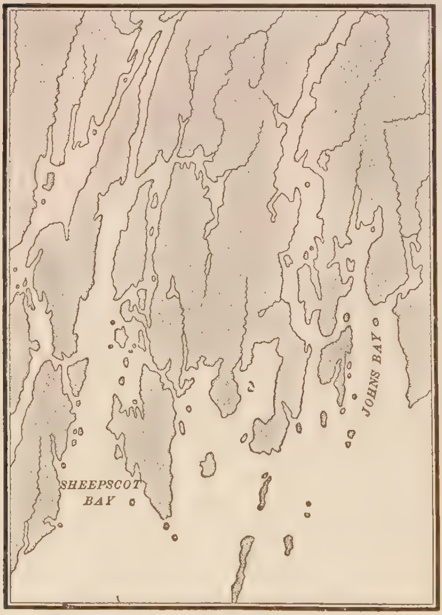


FIG. 218. — Portions of the coast of Maine, showing the effect of subsidence. The valleys have become bays, and the hills peninsulas and islands.

Another characteristic of a sunken coast is the existence of submarine valleys. On the coasts of Europe and North America soundings have shown that the valleys of rivers extend far out on ancient coastal plains (Fig. 219), now the sea bottom. The Hudson River

(Fig. 220), for example, formerly extended across the continental shelf into the deep sea, as is shown by its deep, submarine channel. The St. Lawrence, Potomac, and other rivers also have submarine channels. The bays of the Coastal Plain are the result of a slight subsidence after the newly made land had been cut up to some extent by streams, and are consequently merely drowned valleys. Bays are sometimes formed by the elevation of the sea bottom on one or two sides of an area in which there was no such movement. The Gulf of California had such an origin. Bays are made also by the settling of great blocks (fault blocks, p. 267), as is true on the coast of the Red Sea.

FIG. 219. — Chesapeake and Delaware bays are drowned river valleys, the ancient submerged channels of which can be traced out to sea. (After Dryer.)

FIG. 220. — Map showing the submerged channel of the Hudson River. This channel can be traced about 125 miles beyond the present mouth of the river. (After Dryer.)

Examples of Irregular Coasts. — The character of irregular coasts depends upon several factors.

Coasts of Folded Regions. — If the region is folded, with the axes of the folds parallel to the coast, the bays and islands will have a like direction. A typical example of such a coast is to be found on the northeast shore of the Adriatic Sea (Fig. 221), with its elongated islands, its constricted straits, and narrow bays; all of which are parallel to the coast. When the folds are perpendicular to the shore, a rugged coast with projecting points and deep indentations results (Finisterre, Spain).

Fiord Coasts. — The coasts of high, glaciated regions are characterized by narrow, branching bays of great depth (p. 226, and Fig. 150), with precipitous, almost vertical sides, called *fiords* (p. 166). It has been shown (p. 167) that fiords are valleys greatly deepened by glacial erosion, which have probably been drowned by a sinking of the land. Fiords occur only in high latitudes.

Deeply Indented Coasts in Non-glaciated Regions. — In northwestern Spain, Brittany, Ireland, and elsewhere are fiord-like coasts which, however, have not suffered from glacial erosion. These funnel-shaped bays were produced by the drowning of deep valleys formed by stream erosion. Such indentations differ from fiords, not only in their origin, but also in their V-shaped cross section and in the fact that they gradually deepen seaward, while the deepest portions of fiords are some distance inland.

Coasts of Slightly Submerged Coastal Plains. — The coastal plains of the United States have been described (p. 224) as recently raised portions of the ocean bottom. After having been cut up to some extent by erosion a slight submergence occurred, which drowned the valleys, thus forming Chesapeake Bay, Delaware Bay, etc.

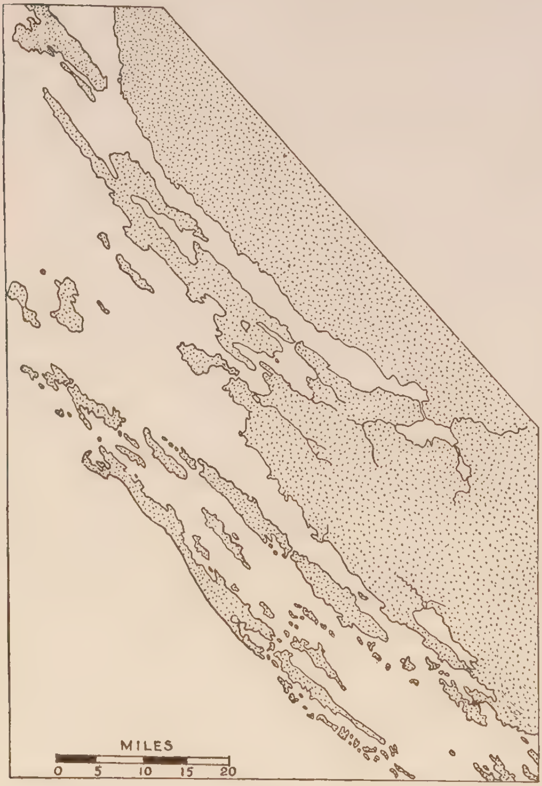


Fig. 221. — Portion of the east coast of the Adriatic. The folds of the rock largely determine the direction of the straits, islands, and peninsulas.

Proofs of Elevation and Depression. — Although the coast of Maine is quite typically that of a region of submergence, there is evidence that considerable elevation followed the period of greatest sinking. This evidence is to be seen in the marine clays which are found above the present sea level, as well as in the abandoned shore lines which are now far above the tide.

The Island of Capri, off the coast of Italy, offers an unusual example of submergence within historic times (Fig. 222). In ancient times a sea cave, now known as the Blue Grotto, was used by the Romans as a resort from the oppressive heat of certain seasons. In order to obtain light an opening was cut in the roof. Since that time the land has sunk so that even the artificial opening is now partly submerged. The blue color of the grotto is due to the refraction of the sun's rays in the water, by means of which the red rays are lost.

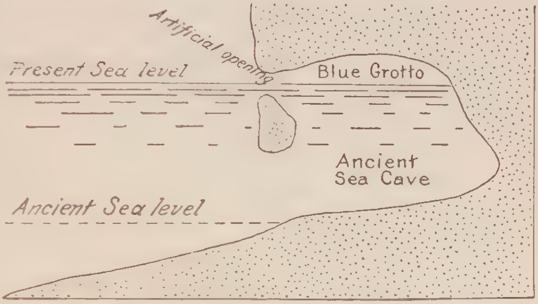


FIG. 222. — Section of the Blue Grotto, Island of Capri, showing proof of subsidence. (Modified after Von Knebel.)

In some of the caves of the Bermuda Islands (Fig. 223), stalactites hang from the roof and extend into the sea water which partially fills the caves. Stalactites obviously could not have been formed in water and therefore prove the former greater elevation of the island.

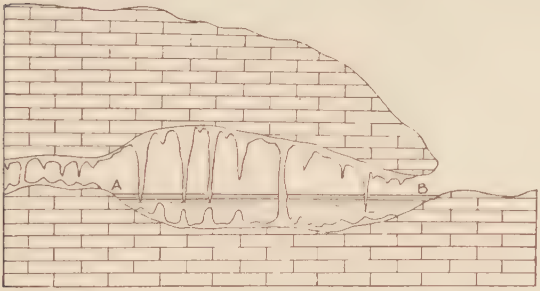


FIG. 223. — Diagrammatic section through a cave in the Bermuda Islands, showing one proof that subsidence has taken place. Stalagmites and stalactites are formed only in the air.

The temple of Jupiter Serapis at Pozzuoli, near Naples, proves that the coast has suffered, first an elevation, then a depression, and finally a reëlevation almost to its former level. The evidence is to be found in three columns of the temple, whose surfaces have been roughened for a height of from 12 to 21 feet above the base by boring mollusks (Lithodomus) which live only in sea water. The temple was, of course, built on land. It was then submerged by the sinking of the coast, so that the columns were immersed in the sea to a height of 21 feet above the base. At this time the Lithodomi bored into the stone and made their homes there. The lower 12 feet of the columns were buried in sediment and therefore escaped damage. Later the land was again raised, and the columns are now some distance from the shore (Fig. 224). Such evidence, although interesting as showing recent changes in sea level, is of minor importance as compared with the occurrence of strata containing marine shells at heights of 14,000 feet or more above the sea.

FIG. 224. — Three columns of the temple of Jupiter Serapis near Naples. The dark and rough band above the figure is the portion which was perforated by boring mollusks. The lower portion of the columns was protected by mud and the upper portion projected above the sea.

The Stability of the Atlantic Coast of North America. — The statement often made that the coasts of Nova Scotia, New England, and New Jersey have recently undergone a gradual subsidence and that this movement is still in progress, rests upon the following evidence.[1] Stumps of trees are found in salt marshes; salt water is found overlying fresh-water peat; marshes have increased in size; dikes erected to keep out the tide are themselves covered at high tide; a bench mark at Boston is now three-fourths of a foot nearer the mean level of the sea than when it was placed there three quarters of a century ago. When each case is carefully studied it is found either that the apparent sinking is due to local causes, or that no definite conclusions can be drawn. The evidence from marshes is especially uncertain, because when drained they settle; when sand dunes encroach upon them, they are compacted and their surface is consequently lowered; when a bar behind which fresh-water marshes and forests exist is cut through by waves (Fig. 225), the marsh will be invaded by sea water, the trees will be killed, and salt-water peat may in time cover the fresh-water peat. Changes in the direction or velocity of ocean currents may also bring about local differences in sea level. The apparent lowering of the bench mark near Boston is doubtless due to the narrowing of the bay as a result of the artificial filling in of the marshes. Such a constriction of the channel would

---

[1] For a more complete statement see: D. W. Johnson, *Science*, Vol. 32, 1910, pp. 721–723, and *Fixité de la Côte Atlantique de l'Amérique du Nord*, Annales de Géographie, Vol. 21, 1912, pp. 195–212.

increase the height of the tides. A recent study of the evidence for and against subsidence of the Atlantic coast indicates that a subsidence of one foot during the last century is impossible.

FIG. 225. — Map showing the conditions which sometimes give rise to the belief that a coast has sunk. If the bar is cut through by the waves, salt water will invade the fresh water marsh and kill any trees which may be growing on it, and salt-water peat may in time cover the fresh-water peat. (After D. W. Johnson.)

In other parts of the world submergence and elevation are certainly taking place. In Sweden careful measurements show that certain portions are rising and others sinking.

Cycle of Shore Erosion. — If one takes into account the combined effects of erosion and accumulation on coasts, it will be seen that all coasts tend to become simple. A coast recently formed by the advance of the sea (submergence of the land), as has been seen (p. 226), has many irregularities, with promontories corresponding to the hills and bays to the depressions. At first the effect of the waves is to render the coast even rougher than it originally was, by the formation of stacks and rocky islets. The effect of difference in hardness is, however, of short duration. A hard stratum may be isolated for a time, but it is an unstable situation, and the islet or point thus formed is destined after a short delay to disappear; marine erosion is incapable of penetrating several miles inland by the excavation of a softer stratum. In these earlier stages of marine erosion (Fig. 226 *A*, *B*), the coast may also for a time be made more irregular by the formation of sand spits, or incomplete bars, but their further development tends, as has been seen, to the formation of a smoother coast by cutting off the indentations which are thus converted into lagoons and later into marshes. In this early stage, which may be compared to the stage of youth in the evolution of land surfaces, the wave-cut terrace is narrow, and much of the shore drift is carried into deep water, out of reach of the littoral currents. The coast of Maine is in general in the youthful stage. The east coast of Scotland is also in early youth, while the Baltic coast of Germany is typical of later youth.

After prolonged erosion the marine terrace is widened, both by the cutting back of the shore and by the outbuilding of the wave-built terrace, and the littoral currents have a broad road over which to move the shore waste. As a result the heads of the smaller bays are filled with sand and pebbles, the larger bays are closed by bars back of which delta deposits are built out, and the rocky islets and stacks are cut away. When the coast is straighter and the marine terrace is so wide that the waves have lost their ability to continue effectively their work of cutting back the land, the shores may be said to be in old age.

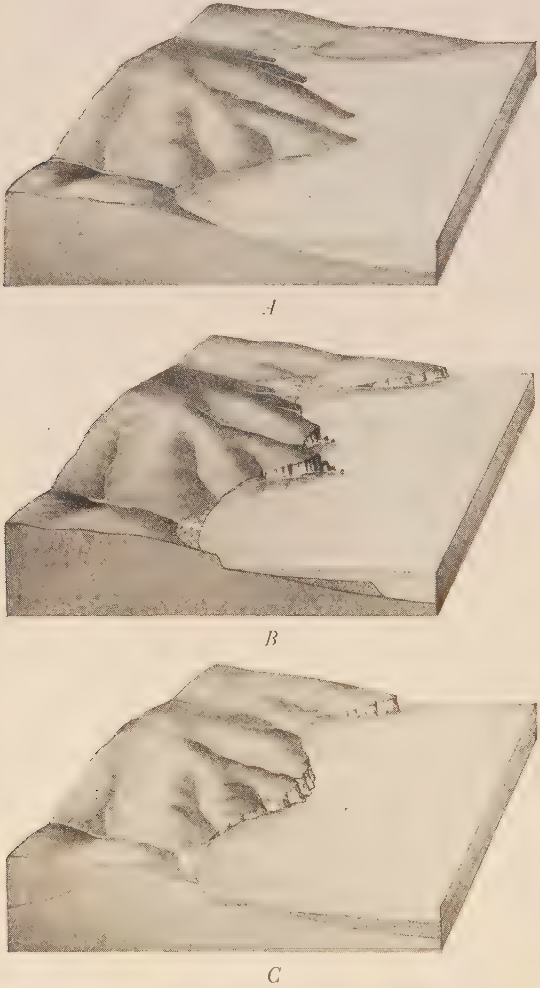


Fig. 226. — Three block diagrams showing the effect of marine erosion. Diagram *A* is the shore which would result if a portion of western New England were lowered 1000 feet. Diagrams *B* and *C* are later stages of the same region, showing the supposed effect of marine erosion on such a coast. Since the shore shown in *C* is relatively stable it is said to be *mature*.

The intermediate stage, maturity (Fig. 226 *C*), is reached when the effective work of the waves is at its height; that is, when the sea is attacking the land along a continuous and nearly straight line of cliffs such as one finds on the northwest coast of France to-day. Such coasts, however, are somewhat irregular, because the shores are usually composed of heterogeneous materials, and also because all parts are not equally attacked by the waves.

The rate at which coasts develop depends both upon the character of the rocks of which they are composed and upon their exposure to the waves. The rate is also affected by the amount of sediment carried in by streams, since if the quantity is large, so much of the energy of the waves and currents is expended in removing it that the shore is but slightly attacked. An excellent example of possible difference in the rate of erosion is to be found on the coast of New England, where the rocky coast of Maine is still in youth, while the coast of Cape Cod, composed of soft glacial material, has been attacked more effectively and is well advanced toward maturity.

Deposition in Seas and Lakes

Source and Extent of Land-derived Sediments. — The sediments carried to the ocean by the streams and the fragments broken from the shores by the waves are soon deposited on the sea bottom and for the most part do not reach a greater distance from the shore than ten miles, although some are carried to the edge of the continental shelf. Some material for these deposits is also furnished by glaciers and the winds. Sediments are, however, swept out by the currents of great rivers, such as the Amazon, Ganges, and Orinoco and deposited several hundred miles from their mouths, as is shown by fine sediments dredged from the sea bottom 200 to 800 miles from the shore. There are two principal reasons for this comparatively narrow belt of deposition. The most important, as already noted (p. 130), is that all sediments sink shortly after reaching quiet water; and the other, that fine sediments settle more rapidly in salt water, very fine silts settling in salt water in one fifteenth the time that they do in fresh water.

Stratification. — Deposits in any one place seldom accumulate to a great thickness under exactly similar conditions and are consequently in layers (Fig. 227); that is, they are *stratified*. Stratification is produced (1) usually by a change from time to time in the character or composition of the sediment. For example, if the deposition of clay is interrupted for a short time during which currents bring in sand, the beds of clay will be separated by layers of sand. (2) If, after a layer of sand has been laid down, deposition ceases for a time and the grains of sand become cemented together to some extent, the succeeding layer of sand will be separated from the underlying by a surface which in this case will divide two beds of similar character. These planes are called *bedding planes*. Slight and frequent changes in the character of the sediments during deposition produce thin layers called *laminæ*. Laminæ are often rendered distinct by the weathering of the rock. Stratification is so characteristic of sedimentary rocks that " stratified " and " sedimentary " are used as synonymous terms in describing rocks of this origin.

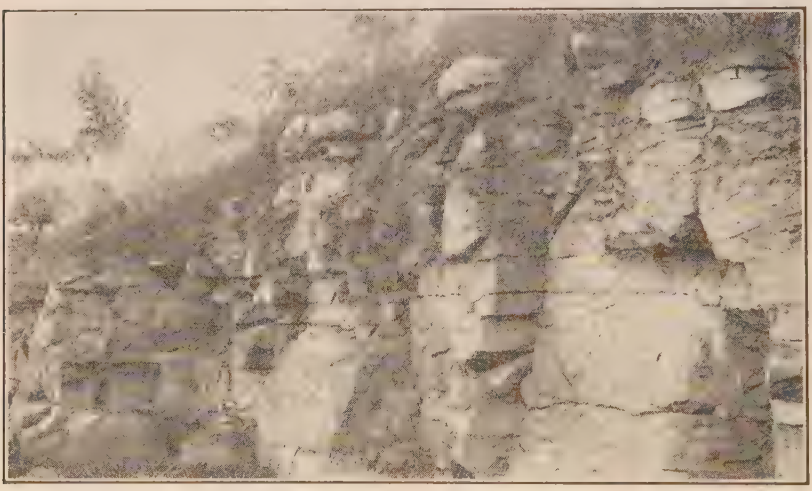


FIG. 227. — Stratified limestone. Auburn, New York. (Photo. H. L. Fairchild.)

Cross or False Bedding. — When sand moved either by air or water currents is carried along a surface which terminates in a slope, the greater part of the material will roll down the slope and come to rest at a steep angle, a steeper slope being made by coarse than by fine sand. If now the direction and velocity of the currents vary, the inclined laminæ will slope or dip in different directions and meet at various angles, producing *cross-bedding*. Cross-bedding is especially well-developed in wind-blown deposits (p. 48), where the shifting winds blow the sand in one direction over an abrupt slope at one time and in a different direction at a later time (p. 47). It is also common in delta deposits, where the distributaries of the river vary from time to time (p. 131). Currents produce cross-bedding near shores and on bars, since the sand which they carry over the end of the embankments is brought in from slightly different directions at different times. The variation in the direction of the waves of succeeding storms often produces a cross-bedding very characteristic of littoral deposits. When the direction of an air or water current changes, the tops of the cross-bedded layers are often eroded away. Later other cross-bedded layers may be laid down on this erosion surface. The upper and lower surfaces of a bed of sand may be parallel with each other, as well as with the bottom upon which they rest, yet the laminæ of which it is composed may be inclined at an angle of 30°, or more (Fig. 228).

FIG. 228. — Cross-bedded eolian sandstone. (U. S. Geol. Surv.)

LITTORAL DEPOSITS

Extent. — Littoral deposits are those which accumulate on that portion of the shore which is exposed between high and low tide, and during exceptional storms or tides above high-water mark. They are most extensive in estuaries where the salt marshes are flooded at high tide, the breadth depending upon the slope of the bottom and the height of the tide. The average width of the beaches of the world does not exceed one half mile, and it is estimated that the littoral belt covers an area of 62,000 square miles. The seaward limit is seldom sharply differentiated, since the deposits grade into those of the shallow sea, although sand, gravel, and shingle usually mark the outer surface of the beach.

Character of Littoral Deposits. — The deposits of this zone vary greatly on different parts of the same coast. Muds are most common in lagoons and in sheltered spots, and bowlders and shingle prevail along rocky shores. The sand of beaches is usually composed of quartz grains, since this is the most common mineral of the rocks of the earth's crust. Another reason for the predominance of quartz is the fact that when rock fragments are rolled about by the waves, the softer minerals of which they are composed are soon ground to fine powder and carried away by even slight currents, and finally deposited as clay, the harder constituents only being left as sand. Locally, sands of other compositions than quartz occur. Occasionally garnet or magnetite grains constitute the chief material of beaches; in the Bay of Naples the sand is made up of the olivine and feldspar derived from volcanic rocks; the sand of the Bermuda Islands is composed of minute shell fragments.

FIG. 229. — Wave ripples on sandstone. (Photo. H. L. Fairchild.)

Distinguishing Characteristics of Littoral Deposits. — Certain features are characteristic of littoral deposits and are due to the fact that these are alternately covered by water and exposed to the sun and wind. Ripple marks (Fig. 229), made by the wind or water; rill marks (Fig. 230), formed by the water as it flowed back down the beach at low tide; rarely sun cracks (Fig. 231), formed by the drying of the mud; raindrop impressions, footprints of animals,[1] and fossils of land and sea animals and plants characterize

---

[1] Sun cracks, raindrop impressions, and footprints are more common on flood plains and playas.

deposits of this origin. Such impressions cannot be retained on a beach unless deposits are accumulating on it; otherwise the record of one day would be obliterated by the tide or waves of the next. The presence of these characteristics of littoral deposits affords evidence that certain ancient rocks were deposited in the littoral belt.

FIG. 230. — Rill marks on a modern beach. They resemble, and in ancient beds have sometimes been mistaken for, seaweed impressions. (U. S. Geol. Surv.)

The thickness to which littoral deposits accumulate depends upon whether the coast is stationary or is sinking. If the subsidence is slow and of long duration, the deposit may accumulate to a great thickness; hundreds and even thousands of feet of sediments having been deposited in this way in the past.

SHOAL-WATER DEPOSITS

Extent and Character of Deposits. — Shoal-water deposits extend from the outer face of the littoral deposits to a depth of about 600 feet, and to a distance of 100 or more miles from shore, that is to the outer edge of the continental shelf (p. 195); and cover an area of about 10,000,000 square miles. They pass almost imperceptibly on the one hand into the coarser littoral deposits, and on the other into the fine deposits of the deep sea. They are similar in character to the littoral deposits, but are finer. Shoal-water deposits, in common with those of the littoral zone, are often ripple-marked and preserve the tracks of such animals as worms and shellfish. Sun cracks and the tracks of land animals are absent. Cross-bedding (p. 235) is often well developed in the sand near shore where horizontal stratification was interfered with by currents (Fig. 228). In general it may be said that these sediments are coarsest near shore and become progressively finer away from it. The reason for this is evident, as the following example shows. When a river enters the sea the force of its current is immediately checked, and the coarser sediment which it carries is deposited, sand is swept out to a greater distance and spread over a wider area, while the fine clay travels still farther and covers a much larger tract of the sea bottom. The sediments moved by the waves and ocean currents are similarly affected; shingle and gravel accumulate close to shore, sand is carried farther out, and clay is most widely spread.

FIG. 231. — Mud or sun cracks. (U. S. Geol. Surv.)

Limestone. — Beyond the reach of the clay lime ooze accumulates. This statement should not be taken to mean that limestone may not accumulate near shore. Near coral reefs lime carbonate is accumulating to-day, and there is much reason to believe that during certain periods of the past, limestone of great thickness was deposited near shores which bordered lands so low that the streams were able to bring to the sea little besides the lime carbonate which they carried in solution. Although lime-secreting organisms are found at all depths of the ocean, yet the most important and abundant are not found at depths greater than light can penetrate (p. 197).

Mud and sand are mechanical or clastic (Greek, *clastos*, broken) sediments; that is, they are derived from the decay of rocks and are brought directly to the sea by streams or by waves. Most of the calcium carbonate which has accumulated to form limestone was, on the other hand, brought to the ocean in solution. Some of it was precipitated directly from the water, since salt water is capable of holding a smaller quantity of calcium carbonate in solution than fresh water. The massive gray submerged limestone off the south coast of England contains modern shells, proving that precipitation is now taking place. Calcium carbonate is also precipitated by the ammonium carbonate derived from the decay of organisms.

The most common limestones are formed from the accumulations of the remains of mollusks, corals, sea urchins, starfish, crinoids (p. 430), Foraminifera (p. 523), and other marine animals, and of certain plants (calcareous algæ). One sometimes sees ledges of limestone almost completely made up of a jumble of shells of one or two species of mollusks. Limestone often shades imperceptibly into shale or fine sand.

We consequently find in ancient rocks that conglomerates (p. 249) usually occur in relatively narrow belts, and sandstones often cover wide areas, while shales and limestones have a still wider distribution.

Lens-shaped Sediments. — All sedimentary deposits are roughly lens-shaped. They are thickest as well as coarsest near the source of supply, and become finer and thinner away from it. This is most noticeable in conglomerates (p. 249) which in a distance of even two or three miles may decrease from a thickness of perhaps several hundred feet to that of a few feet, or may disappear entirely. Sandstones have a similar character, but usually thin out much less rapidly; while muds, or their equivalents, shale and limestone, may extend many miles with slight variation in thickness. Beds of limestone only a few feet thick can sometimes be traced over an area of several hundred square miles.

Dovetailing of Sediments. — If a boring were made a few miles from shore, through sediments which had accumulated to a considerable thickness, it would seldom penetrate a single kind of rock for a great depth, but would, for example, first pass through sandstone, then shale, then sandstone again, and perhaps through limestone.

If these beds were traced from the shore outward it would be found that, as in the diagram (Fig. 232), the sandstones projected as a thin wedge between layers of shale. This "dovetailing" is due to temporary changes in the conditions of sedimentation. During violent storms sand or even gravel may be carried out much farther from shore than usual, but when calmer weather prevails mud will be laid down on the sand and gravels. During severe floods rivers also bring down an enormous quantity of sediment which is swept a much greater distance into the sea than normally.

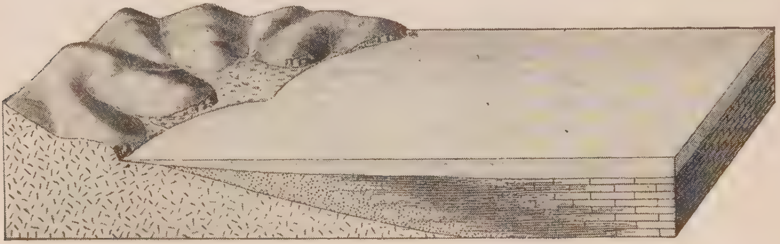


FIG. 232. — Dovetailing of sediments. As sediments are traced from the shore their character usually changes gradually. The dovetail structure is due to shifting conditions; heavy storms carry coarse material to an unusual distance, and calm weather permits the deposition of fine sediment close to shore.

Basal Conglomerates. — If a coast is sinking more rapidly than it is filled by sediments the shore will gradually retreat inland, with the result that the beach of one period becomes deep water later. The coarse sediment of the submerged beaches will be covered by finer sand, muds, and lime, the nature of the deposit depending largely upon the distance from shore. These gravels which cover the old land surface, when hardened (indurated), are called *basal conglomerates* (Fig. 233).

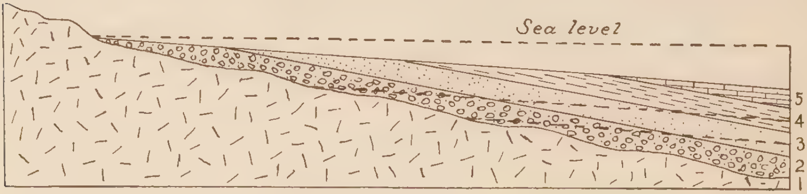


FIG. 233. — Basal conglomerate. When the old land surface (1) was slowly submerged, gravel (2) was deposited along the shore and as a result of progressive subsidence covered the ancient land surface. The strata (3), (4), and (5) were deposited upon the gravel (basal conglomerate) as the distance from the shore increased. Contemporaneous deposits are shown by the dotted lines 3 and 4.

Subsidence Necessary for Great Accumulations. — Sediments do not accumulate to a great thickness unless the sea bottom upon which they are being laid down is subsiding. This has not been an uncommon condition in the past, as is shown by the occurrence of stratified rock four and even more miles in thickness. Many of these deposits are of shallow-water or of continental origin, as the ripple and rill marks, the coarseness of some of the ingredients, and the fossils show.

DEEP-SEA DEPOSITS

Deep-sea deposits cover about three fifths of the sea bottom, and are found beyond the limit of the sediments derived from the land.

Blue Mud. — Since an ocean depth greater than 600 feet is usually more than 10 miles from the shores, only those sediments which are so fine that they can be carried in suspension for a long distance are found in such situations. The sediments are usually of a bluish gray color and are classed roughly as *blue muds*. The bluish gray color is due to the fact that the contained organic matter prevents the oxidation of the iron in the deposits. They cover an area of approximately 15,000,000 square miles of the ocean bottom, or five times the extent of the United States. They surround all coasts, beyond the shoal deposits, and cover the deeper parts of such inland seas as the Mediterranean. The depth of water in which they occur varies from about 750 feet to 16,800 feet.

Globigerina Ooze. — This ooze is a deposit consisting of 30 to 90 per cent. of the shells of Foraminifera (Fig. 234), of which the most abundant genus is *Globigerina*. These unicellular animals seldom attain a size greater than that of a pinhead, and secrete a shell (test) of calcium carbonate. They are extremely simple in structure, but the shells as seen through a microscope are very beautiful. They live in countless millions in the surface and subsurface waters of the ocean and upon their death rain down on the sea floor. It is not to be understood that these organisms are the only ones whose remains constitute this widespread deposit. Other small forms of life, which also live in

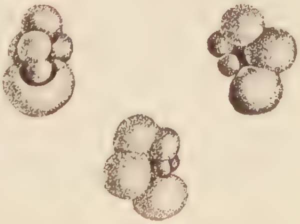


FIG. 234. — Globigerina ooze, greatly magnified. (After Shimer.)

great abundance at the surface, likewise add to the deposit after their death. Foraminifera are not more abundant over the deeper waters than over those nearer shore, but the deposits formed from their remains are not recognizable in the latter, because of the large percentage of land sediments with which they are mixed. Globigerina ooze is seldom found in water more than one to two miles deep. Below a depth of 15,000 feet the proportion of calcareous deposits diminishes, owing to the increase in the percentage of carbon dioxide in the water which dissolves the shells. However, many millions of square miles (probably 49,520,000) of the ocean floor in temperate and tropical regions are being covered by deposits of globigerina ooze to-day. The chalk of England and of the western United States is composed largely of the remains of Foraminifera, although the remains of other animals are not uncommon (p. 249).

Radiolarian Ooze. — Other unicellular animals which secrete siliceous shells (Radiolaria) form *siliceous oozes*, but are found in bottoms at a greater depth than the globigerina ooze, in some cases where the ocean is five miles deep.

Red Clay. — At depths greater than 15,000 feet, as has been seen, the calcium carbonate of the Foraminifera is dissolved; consequently below this depth enormous areas of the ocean floor are covered with extremely fine, reddish clay, composed of the insoluble portion of Foraminifera, volcanic dust, pumice, ash, and minute meteorites. Radiolarian ooze and red clay shade into each other in certain places, the deposit being called radiolarian ooze when these organic remains constitute 25 per cent. of the mass. The color of red clay is due to the presence of iron oxide (Fe_2O_3) formed by the oxidation of iron and iron compounds. This deposit covers an area of 51,500,000 square miles, four fifths of which is in the Pacific Ocean, the smaller area in the Atlantic being due to its lesser depth.

The slowness with which red clay has been deposited in the past is perhaps best shown by the number of sharks' teeth that are dredged from the bottom. In a single haul in the south Pacific 1500 sharks' teeth were brought to the surface, many of which were of extinct species. It has even been suggested that, were all of the sharks alive whose teeth rest upon certain areas of the ocean floor, the ocean immediately above these deposits would be filled from top to bottom with living flesh. The fact that meteoric dust which gathers with extreme slowness can be detected in these deposits is a further evidence of the great slowness with which the red clay accumulates.

It is interesting to note that no deposits of this sort have ever been found on the continents, showing perhaps that the great depths of the ocean have never been raised to form dry land. It is rare that any rock is found on the continent which implies water deeper than a few hundred feet.

Coral Reefs and Islands

Coral islands have long excited the interest of mariners, both because of their location far from land and because of their beauty. They are also of great scientific interest because of their origin.

Reef-building corals grow best in seas (1) with a minimum temperature of not less than 60° F.; (2) at a depth of not more than 150 feet; (3) where the salt water is free from sediment; and (4) where they are exposed to the dash of the waves. Free exposure to the waves is of advantage, since the profusion of life on a coral reef soon exhausts the oxygen needed for respiration and the calcium carbonate necessary for their stony structure. Since they do not thrive in muddy or fresh waters they are not developed near the mouths of rivers.

In tropical regions where the above favorable conditions prevail, the shores of the continents are bordered by coral reefs, called *fringing reefs*, which have a steep slope of 50° to 60° on the seaward side. In many cases in addition to the fringing reef there is another reef, surrounding the island or paralleling the land, several miles from shore. Such a reef is termed a *barrier reef* (Fig. 235). Circular reefs or atolls, without islands in the center, and *lagoonless coral islands* also occur.

FIG. 235. — Barrier reef off the coast of the island of Curaçao, Dutch West Indies.

The geological importance of coral animals lies in the fact that they have the power of extracting calcium carbonate from sea water and depositing it within their own bodies. Upon the death of the animal this "skeleton" is left as a firm calcareous deposit. The reef-building corals live principally in colonies and because of this assume many forms; some are in great head-like masses (brain corals), others are branching like trees (staghorn corals), while others are in flat masses.

Coral reefs are not built up entirely of the remains of coral animals, but a large part is contributed by other lime-secreting organisms which live in association with the corals. These reefs are not built above the level of the water by the coral animals, but by storm waves which tear masses of coral from the reef and pile them up above sea level. The building above the sea is thus seen to be accomplished in the same way as is the formation of sand reefs (p. 221). As soon as the broken coral rock is above the sea, some of it is dissolved by rain water and spray, and upon being redeposited cements the fragments into firm rock. The coral reefs thus built above the sea are consolidated into compact limestone.

The most extensive barrier reef in the world is the Great Barrier Reef of Australia which borders the coast of that continent for about 1000 miles at a distance of 20 to 50 miles from the mainland. Its breadth beneath the surface of the sea varies from 10 to 90 miles, although but little is exposed above the water. The channel between the Great Barrier Reef and the shore is from 60 to 240 feet deep, but the outside of the reef has a steep slope, so that in short distances depths of 1800 feet are encountered. This difference of slope on the two sides is due to the fact that growth on the outside is better assured, as it receives the full sweep of the waves, so that aëration is better realized there, food is more abundant, and the washing away of dead parts more quickly accomplished. This rapid growth toward the open sea causes a very jagged contour and an abrupt slope.

Coral-reef Problem. — The origin of fringing reefs is evident, since all of the conditions favorable to coral growth, such as a warm temperature, a depth of water not greater than 150 feet, and free exposure to the waves, are present on portions of the shores of the islands and continents of the tropics, or where the ocean currents bring water with a temperature of at least 68° F. The origin of barrier reefs, atolls, and lagoonless islands is not so clear, since barrier reefs are separated from the land by channels sometimes several miles wide and from 120 to 180 feet deep, and the lagoons of the atolls sometimes have a depth of 350 feet.

Subsidence Theory of Darwin. — This theory holds that on a slowly sinking island (Fig. 236) a fringing reef would be built to the surface by the accumulation of the calcareous remains of the corals and other animals, and plants which flourish under similar conditions. It is apparent that since corals grow best on the outside of a reef where the waves beat freely and there is an almost complete absence of sediment, a fringing reef would in time, if the sea bottom slowly subsided, become a barrier reef, separated from the island by a lagoon.

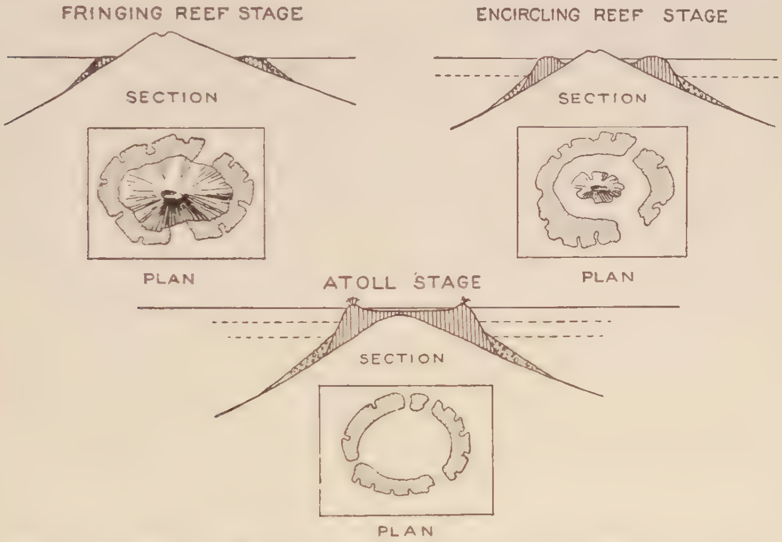


Fig. 236. — Diagram illustrating Darwin's theory of coral islands, showing the fringing reef stage before subsidence, the encircling reef stage after some subsidence (dotted line), and the atoll stage after the island had been completely submerged.

It is also readily seen that under such conditions the lagoons would become deeper and wider as the subsidence proceeded. The distance of the barrier reef from the island, under these conditions, would depend upon the slope of the island and the amount of sinking. If subsidence continued, the peak of the original island would eventually disappear and an atoll would be left. The following have been offered as proofs of this theory. Islands surrounded by barrier reefs are characterized (1) by an embayed shore line which, as has been seen (p. 228), indicates subsidence; (2) by the absence of delta plains in the indentations, such as would be present if the island had stood at the same level for a long period of time; and (3) by ridges that do not end in sea cliffs, as would be the case if a volcanic island had been cut back by the waves to form a marine platform upon which the corals grew. (4) It has also been found that borings of 1000 or more feet penetrate materials like those of the superficial layers of the reef. Also, according to this theory, the barrier reef gradually contracts as subsidence continues, resulting, if the sinking has been long continued, in the complete drowning of the island and the formation of an atoll and finally of a lagoonless island.[1]

Submarine Bank Theory of Murray and Others. — This theory holds that barrier reefs and atolls may be explained without postulating subsidence of the sea floor. The supporters of this theory believe that banks may be built up by the accumulation of the remains of marine animals until a depth of water suitable for coral growth is attained, or a platform for the corals may be formed by volcanic cinder cones (such as that of Graham's Island).

Since coral growth is most rapid on the outer margin of such a bank or cone, a ring arises with a lagoon within. Waves break through the ring, separating it into a series of islets, and the solvent action of sea water together with the erosion of currents deepens and widens the lagoon. According to this theory the coral ring grows larger; according to the subsidence theory it becomes continually smaller. In support of this theory it is pointed out that elevated atolls are sometimes mere skins on older volcanic rocks and are not of great thickness. In many cases, moreover, coral atolls rest upon limestone and volcanic rock which have been cut down by erosion and have not sunk. The most serious objection to this theory is that sediments carried into the lagoons by streams from the islands have not built delta plains, as would be the case had the region suffered no subsidences. Some atolls have probably been formed in this way, but the general application of the theory is not justified.

Change in Sea Level Due to Glaciation, or the Glacial-control Theory. — An ingenious theory elaborated by Daly is based upon the lowering of the level of the sea in the tropics, due to the withdrawal of the water in those regions by evaporation, and its later precipitation in the north as snow during the formation of the great (Pleistocene) ice sheets; this withdrawal being increased by the attraction of the water by the great mass of ice in the Arctic regions. "The ice sheets (Pleistocene) which have since melted

---

[1] Davis, W. M., — *Nature*, Vol. 90, 1913, pp. 632–634.

away had a combined area of at least 6,000,000 square miles, with an average thickness of probably more than 3000 feet. The removal of enough water to form that ice tended to lower sea level all around the globe at least 150 feet. The gravitative attraction of the ice caps must have further lowered the equatorial seas by amounts ranging from 30 to 50 feet. The net shift of level in the equatorial zone was, therefore, at least 180 feet. Conversely, the melting of the full 6,000,000 square miles of ice must have raised sea level in that zone about 180 feet."[1] The cooling of the climates and waters of the world during the Glacial Period (p. 644) retarded, or entirely stopped, the growth of reefs over a large part of the world. Having lost their defending reefs by this temporary change in climate, the islands were vigorously attacked by the powerful breakers of the open sea, resulting in their planation at a depth of a few fathoms below the level of the sea of that time (Fig. 237). With the amelioration of the climate, the ice caps of the high latitudes began to melt, and the surface temperature of the equatorial ocean was soon raised to a point which permitted the coral polyps to flourish. These animals speedily colonized the eroded platforms and developed the atoll form as the result of *the slow rise of sea level.*

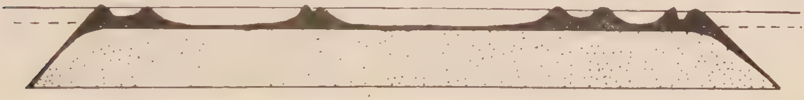


FIG. 237. — Diagram illustrating the glacial-control theory of coral islands. The platform rock is shown by dots, the coral reef and calcareous débris by solid black. The level platform is thought to be a plain of marine denudation cut when the sea level was lowered by the withdrawal of water to form the great ice sheets of Europe and North America. The coral islands were slowly built up as the level of the sea was raised upon the melting of the glaciers. (After Daly.)

As proof of this theory it is pointed out that the platforms upon which the reefs rest are remarkably flat, *as if planed by marine erosion*, and that they have a nearly uniform depth of 275 feet, *i.e.*, a depth of about 95 feet below the level of the seas of glacial times. It will be seen that Darwin's and the Penck-Daly theories differ principally in that, in the former, the land is believed to have slowly sunk, while in the latter, the sea level is thought to have been gradually raised.[2]

---

[1] Daly, R. A., — *Pleistocene Glaciation and the Coral Reef Problem*, Am. Jour. Sci., Vol. 30, 1910, pp. 297–308.

[2] Daly, R. A., — *Science Conspectus*, Vol. 1, 1911, pp. 120–123.

CONSOLIDATION OF SEDIMENTS

The greater part of the surface of the continents of the world is composed of sedimentary rocks which were originally laid down in the sea. These were at first largely unconsolidated gravels, muds, and calcareous oozes, but are now usually thoroughly consolidated. In general, it may be said that the more recent rocks are not as firm as those of greater age. For example, the rocks[1] of the coastal plains of the United States (p. 574) are sands and clays which are almost or quite as soft as when first laid down; while in other portions of the continent, where the sedimentary rocks are older, they are usually hard. The consolidation of sedimentary rocks is brought about by (1) cementation, (2) pressure, and (3) heat.

Cementation. — Loose (incoherent) deposits are consolidated either by direct cementation or by the formation of interlocking, fibrous crystals which hold the grains firmly together. Some recently built sand reefs, such as those which border the coast of Pernambuco, Brazil, are already converted into sandstone by the deposition of calcium carbonate between the sand grains. At the mouths of rivers the sediments are sometimes consolidated by calcium carbonate, precipitated from the fresh water as it mingles with the sea water, as rapidly as they are laid down. In deposits composed of fragments of shells, calcium carbonate also constitutes the cementing material. In this case, as has been seen (p. 51), the sediment furnishes its own cement, which is first dissolved from the calcareous fragments and later redeposited a short distance beneath the surface of the deposit, thus forming a more or less compact limestone. In this way the limestone of Bermuda and the " coquina " limestone of the coast of Florida were formed.

Sediments are also cemented by iron oxide which is derived from the soluble salts of iron carried into seas and lakes. These iron compounds upon oxidation sink to the bottom and firmly cement the sand.

Sands composed of quartz grains are sometimes cemented by silica and form extremely hard *quartzites* (p. 344).

Effect of Pressure. — When subjected to the great pressure of overlying sediments, muds are compacted and thus hardened into *shale*. The compactness of shale is also sometimes increased by the

---

[1] The word *rock*, used technically, does not necessarily imply compactness, but includes loose sands as well as granites.

deposition of some mineral matter about the grains. Other sedimentary rocks are also compacted in the same way.

Effect of Heat. — Sediments usually become more compact when subjected to heat, as will be seen in a later discussion (Metamorphism, p. 341).

CLASSIFICATION OF SEDIMENTARY ROCKS

Limestones. — The rocks of this class are composed either of calcium carbonate ($CaCO_3$) or of calcium and magnesium carbonate ($CaCO_3 \cdot MgCO_3$), and are formed in one of the following ways: (1) as a result of chemical precipitation, (2) by the accumulation of the calcareous coverings or skeletons of animals and plants, and (3) from fragments of limestone which have been re-cemented into a solid mass. *Chalk* (p. 523) is a limestone composed, for the most part, of the remains of microscopic animals (Foraminifera). *Oölitic limestone* consists of minute spherical concretions having much the appearance of a fish roe, hence the name oölitic (p. 78). When the little concretions are broken open and examined with a microscope a grain of sand is often found in the center, around which concentric layers of calcium carbonate have been added. Oölitic limestone is widely used for building purposes in the United States, England, and France. *Travertine* is deposited from solution near places where springs laden with calcium carbonate emerge. In the Dinaric Alps travertine forms thick beds and partially fills the basins. Such deposits are not uncommon in North America in valleys of limestone regions, where they occasionally attain a thickness of more than 100 feet. *Dolomite* is a limestone composed of calcium and magnesium carbonate in varying proportions. It is widespread and often of great thickness.

Sandstones. — Under this term are included sandstones and conglomerates. They were derived from the land, and their coarseness or fineness (texture) depends upon their nearness to or remoteness from their source, or upon the swiftness of the currents which transported them. A *sandstone* is composed of fine grains, while a *conglomerate* is made up of gravel and shingle. A *breccia* (Italian, pronounced brĕch′*a*) is a rock composed of *angular* fragments larger than sand, and was formed by the cementing together of the particles of a much fractured or crushed rock, or of talus which had been transported but a short distance and therefore was not worn and rounded.

Shales. — These are consolidated muds which were formerly derived from the decomposition of the feldspars of igneous rocks (p. 330) under the action of the water. They are usually finely laminated (p. 234).

Sandstones and shales, when traced for some distance, may become more and more calcareous, gradually shading into pure limestone, and *vice versa.*

Deposits in Lakes and Deserts. — The deposits of lakes will not be treated separately, since they consist, as in the seas, of clays, sand, and occasionally of gravel, and when consolidated are distinguished with difficulty from marine deposits. Because of their limited extent and the small chance of preservation, they are usually of little importance when compared with the widespread and thick marine deposits. In certain regions ancient lake sediments several thousand feet deep occur. The conglomerates and sandstones of desert regions have been discussed elsewhere (p. 52).

Influence of Sedimentary Rocks upon Topography. — Firmly cemented conglomerates and sandstones are important hill and mountain makers. The "rock cities" of southwestern New York and many of the ridges of the Appalachian Mountains stand in relief because of the presence of strata of resistant sandstones or conglomerates. When pure sandstones disintegrate, they form barren soils which even in populous regions are usually covered with forests, since they are too poor for agriculture. The scenery of limestone regions has already been described (p. 73). In such a land wide joints, swallow holes, and caves are usually common, and the drainage may be entirely underground. When limestone is massive it may be cut down by the streams less rapidly than the neighboring strata, and form high cliffs and mountains. The Helderberg escarpment of eastern New York is a conspicuous line of limestone cliffs stretching for many miles.

Regions underlain by shale are usually low and flat. The wide Mohawk valley of New York; the level, fertile plains of Ontario; the northern Middle States of the United States; and the Black Belt of Alabama are examples.

REFERENCES FOR OCEANS AND LAKES

Arber, E. A. N., — *The Coast Scenery of North Devon.*
Cornish, V., — *Sea Waves.*
Davis, W. M., — *The Outline of Cape Cod:* Geographical Essays, pp. 690–725.

Davis, W. M., — *Home Study of Coral Reefs*, Bull. Am. Geog. Soc., Vol. 46, pp. 561–677; 641–654; 721–739.

De Martonne, E., — *Géographie Physique*, pp. 673–706.

Fenneman, N. M., — *Lakes of Southeastern Wisconsin:* Bull. Wis. Geol. and Nat. Hist. Surv. No. 8, 1902.

Geikie, J., — *Earth Sculpture*, pp. 315–335.

Gilbert, G. K., — *Lake Bonneville:* Monograph, U. S. Geol. Surv., Vol. 1, 1890.

Gilbert, G. K., — *The Topographic Features of Lake Shores:* Fifth Ann. Rept., U. S. Geol. Surv., 1885, pp. 63–123.

Hunter, J. F., — *Erosion and Sedimentation in Chesapeake Bay:* Professional Paper, U. S. Geol. Surv. No. 90-B, 1914.

Johnson, W. D., — *The Atlantic Coast.*

Shaler, N. S., — *The Geological History of Harbors:* Thirteenth Ann. Rept., U. S. Geol. Surv., 1893, pp. 93–209.

Wheeler, W. H., — *The Sea Coast.*

TOPOGRAPHIC MAP SHEETS, U. S. GEOLOGICAL SURVEY, ILLUSTRATING OCEAN AND LAKE SHORES

Bars and Tied Islands	*Drowned Coasts*
Tamalpais, California.	Boothbay, Maine.
Duluth, Minnesota.	Seattle, Washington.
Marthas Vineyard, Massachusetts.	Boston, Massachusetts.
Boston, Massachusetts.	Charlestown, Rhode Island.
Coos Bay, Oregon.	Tolchester, Maryland.
	Point Lookout, Maryland.
	Sandy Hook, New Jersey.

CHAPTER VII

THE STRUCTURE OF THE EARTH

UNLESS subsequently disturbed, the sedimentary rocks of the earth are in the approximately horizontal position which they had when they were first deposited. For example, we find the sedimentary strata covering the vast territory between the Appalachian and Rocky mountains, for the most part, in the horizontal position which they had when they were outspread in sheets on the ocean floor.

STRUCTURAL FEATURES OF ROCKS

Dip and Strike. — In such regions as the Appalachians, New England, eastern Canada, the Rocky Mountains, and the Sierra Nevadas, however, the strata are often inclined at angles varying from horizontal to vertical. The strata thus tilted are sedimentary, and their present attitude is the result of compressional forces to which they were subjected. As a result of weathering and erosion their upper portions were denuded, leaving the inclined beds outcropping at the surface. In Fig. 238 the position of the strata with reference to the present surface is shown, and the portion carried away by erosion is indicated by dotted lines. Two terms are used to describe an inclined bed: *dip* and *strike.* The meaning of the terms can best be understood from an illustration. If one side of the roof of a house is taken to represent an inclined stratum, the downward inclination, that is, the course which water poured on the roof would take, is the *direction of the dip*, the angle of the dip being the departure from the horizontal. Thus, if a roof is inclined at an angle of 30° to a level

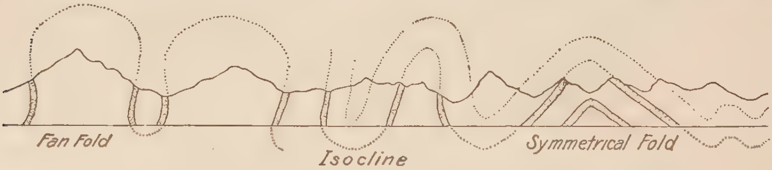


FIG. 238. — Section through a folded region showing a symmetrical fold, an isocline, and a fan fold.

plane, it has a 30° dip; if the angle is 40°, the dip is 40°. The ridgepole of the house extends at right angles to the dip of the roof and corresponds to the *strike* of a stratum which is defined as *the direction at right angles to the dip.* If, for example, a bed dips to the west, the strike is north and south (Fig. 239). The importance of ascertaining the dip and strike of beds is evident in such cases as the following. Suppose a landowner finds that a valuable coal seam *outcrops* a few hundred feet east of his property. If the dip of the bed were found to be 15° west, he would know that the coal seam could also be encountered on his property by sinking a shaft, and the exact depth at which it would be found could be determined by a simple mathematical calculation (Fig. 240). As the angle BAC (dip) is 15° and the angle ABC, a right angle, the angle BCA must be 75°. The length of the side BA can be ascertained by the trigonometric formula, $\tan BAC = \frac{BC}{AB}$, or $BC = \tan BAC \times AB$. If, however, it were found that the *strike* of the coal seam is east and west, the landowner would know that in this case also the coal seam probably extended on his land and was merely hidden from view by soil or glacial drift. A knowledge of the dip and strike of a water-bearing stratum, such as the Dakota sandstone in Nebraska and South Dakota, has enabled those in search of artesian water to estimate the depth to which it is necessary to bore and whether or not a well would flow. It is, however, in determining the structure of a region that the dip and strike are especially used.

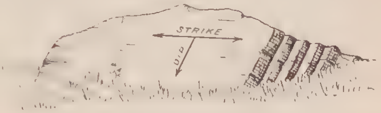


FIG. 239. — Diagram illustrating *dip* and *strike*, the dip being the angle of the greatest inclination of a bed (shown by arrow), and the strike the direction at right angles to the dip.

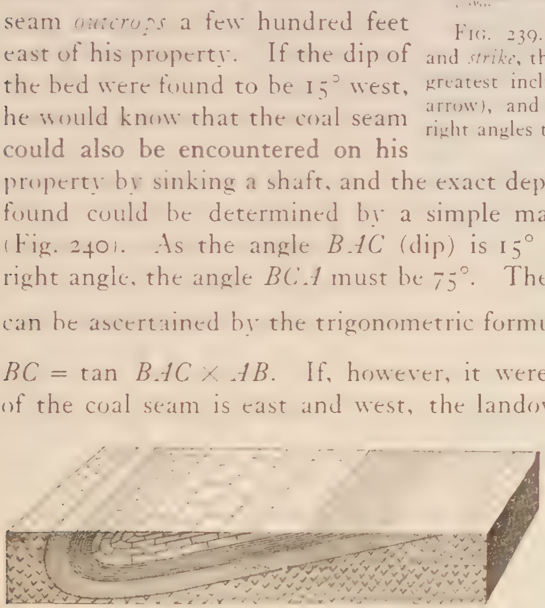


FIG. 240. — Block diagram showing the effect of dip upon the width of the outcrop of strata. The strata at the right are nearly four times as wide as those at the left, although the thickness is the same.

Effect of Dip and Strike upon Outcrop. — When a series of strata are horizontal, only the uppermost appears at the surface; but when the beds are inclined and eroded, each bed in succession outcrops at the surface, the smaller the dip the wider being the outcrop. For example, a bed one foot thick at an angle of 1° on perfectly level ground has an outcrop 40 feet wide; with a dip of 5°, the outcrop is about 11 feet wide; with one of 30°, it is only 2 feet, and when the stratum is on edge (90° dip), the thickness of the bed determines the breadth of the outcrop (Fig. 240).

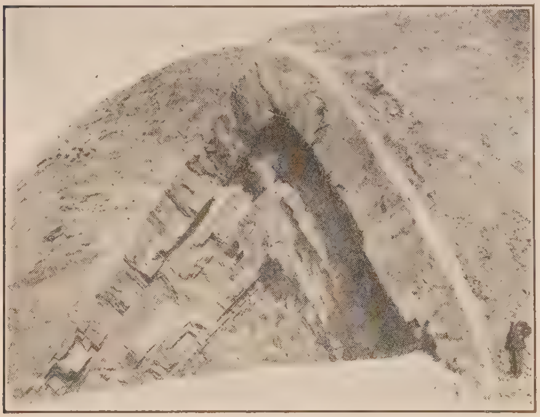


FIG. 241. — A sharp anticlinal fold. (After E. A. N. Arber, *The Coast Scenery of North Devon.*)

FOLDS

When inclined strata are cut by streams or eroded by waves, they are often seen to be arched or in *anticlines* (Fig. 241), or in troughs or *synclines* (Fig. 242). These anticlines and synclines vary in size from a few feet to scores of miles across, and from almost flat arches to such steep ones as that shown in Fig. 348, p. 360. In an anticline the strata dip from both sides of the crest line called the *axis of the fold*, and in the syncline towards the *axis of the trough*. When folds are closely compressed, so that the flanks or *limbs* are approximately parallel, they are called *isoclines*. Folds are not always symmetrical, but, on the contrary, are often unsymmetrical (Fig. 238, p. 252). When they are so inclined that one limb or flank becomes doubled under the

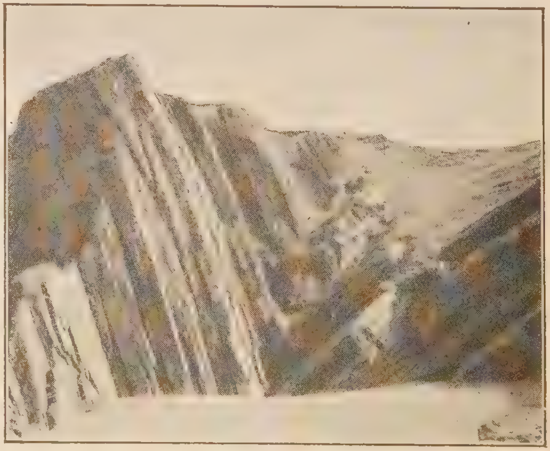


FIG. 242. — A synclinal fold, North Devon, England. (E. A. N. Arber, *The Coast Scenery of North Devon.*)

other, they are called *overturned folds* (Fig. 243 *C*). Folds are called *recumbent* when they are so far overturned that they lie on their sides. The crests of anticlines are often thickened and the limbs thinned. In severe folding this may result in a limb so thin as to be scarcely recognizable. When the compression has been very great, the sides of an anticline may be driven toward each other to such an extent as to produce what is called a *fan structure* (Fig. 243 *D*).

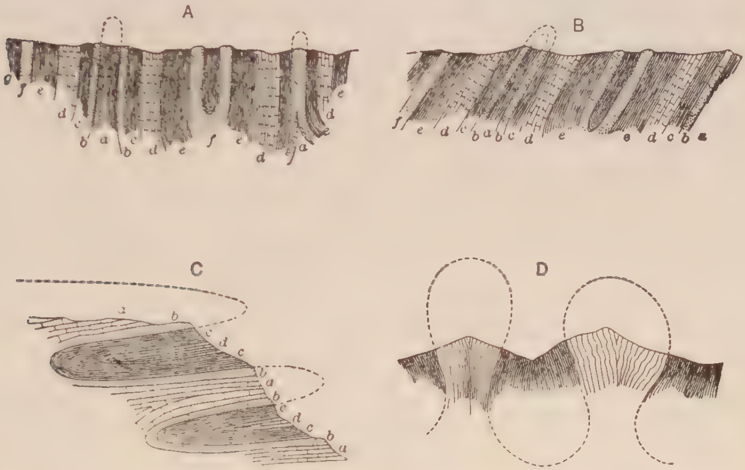


Fig. 243. — *A*, upright isoclinal folds; *B*, inclined isoclinal folds; *C*, overturned isoclinal folds; *D*, fan fold. (Ries and Watson, after Willis.)

The *axis of a fold*, or its crest line, is not horizontal for long

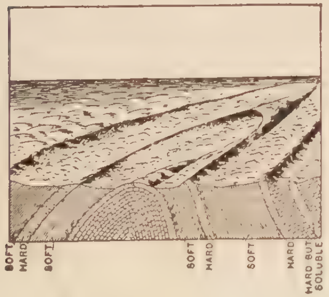


Fig. 244.

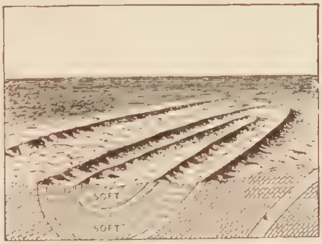


Fig. 245.

Figs. 244 and 245. — Surface and sectional views of a plunging anticline (244) and of a plunging syncline (245). The effect of resistant strata in forming ridges and canoe valleys is shown. (After Willis.)

distances, but is either gently arched, or dips and pitches, the slant of the axis being called its *pitch* (Figs. 244, 245).

Fig. 246. — An anticlinorium. (After J. Geikie.)

One sometimes sees anticlines unaccompanied by synclines, but more often the two occur together. Notable examples of series of great parallel folds are to be seen in the Appalachians of Pennsylvania and in the Juras of Switzerland. In greatly folded regions, indeed, the conspicuous anticlines may be considered as minor crumplings of a great, complex anticline (Fig. 246) called an *anticlinorium*, or of a complex syncline called a *synclinorium* (Fig. 247). A form of fold which, though simple, cannot be included in the term anticline is the *monocline*, or step-fold (Fig. 248). It occurs where horizontal rocks suddenly bend downward. In portions of Utah and Arizona monoclinal folds are not uncommon and often merge into or give place to faults.

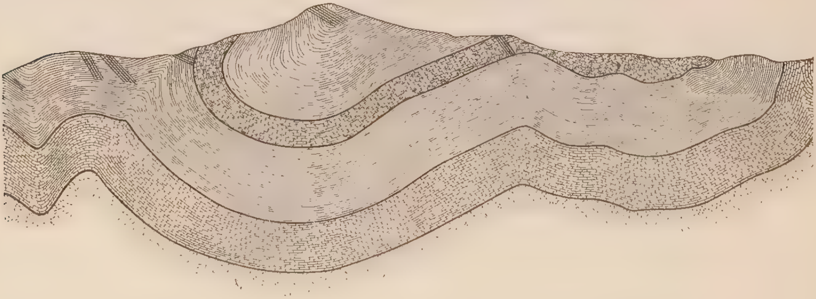


Fig. 247. — The Mt. Greylock, Massachusetts, synclinorium. (U. S. Geol. Surv.)

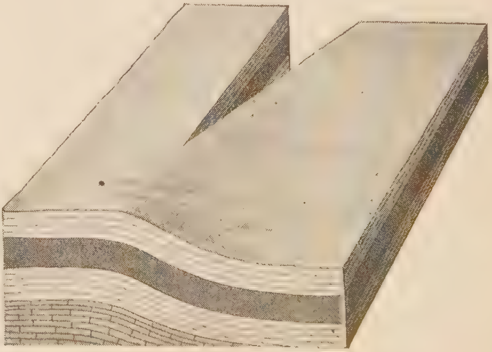


Fig. 248. — Monoclinal flexure and fault.

Effect of Folding on Competent and Incompetent Strata. — If the strata which are being folded are composed of beds of firm sandstone or limestone, they will be thrown into anticlines and synclines. Such strata are called *competent*. If the strata, however, consist of shale or clay, they may not be strong enough to form arches and will be squeezed and crumpled together, and are called in consequence *incompetent* strata. The effect of horizontal compression upon beds of rock differs under different conditions. For example, if a bed is near the surface, it may upon being subjected to lateral pressure be able to form an anticline; but if it is deeply buried, the pressure of the overlying strata may be so great that it will be crumpled into many small folds. No one has ever seen strata in the process of folding, but through experimentation (p. 361) and a study of folded strata the means by which it is produced have become known.

How the Structure of a Region is Determined. — In order to determine the structure of a region in which the strata have been greatly folded and eroded, it is necessary that a geological map of the region be made, in which the areas underlain by the various rocks are indicated and the dip and strike of the outcrops recorded. When such a map as that shown in Fig. 249 is completed, we find that not only does the strike of the beds vary, but that the dip as shown by the arrows varies. By combining all of the data attainable, the cross section also shown on the side of the diagram can be constructed.

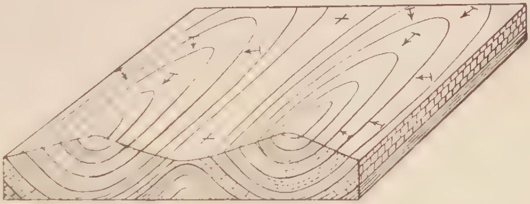


Fig. 249. — Block diagram showing the manner in which geological maps are prepared. The various rock formations are mapped and the dip and strike of the strata (shown by arrows) recorded, in order that the geological section (shown on the sides of the diagram) can be determined.

Origin of Folds. — The origin of folds will be discussed more fully under mountains (p. 358). It will be sufficient at this time to state that the various folds which have been discussed (with the exception of monoclinal folds) are in general due to lateral compression (p. 364).

Warping. — Besides the folding described above there are movements of the earth's crust which result in the *warping* of its surface; that is, there are vertical movements which raise the surface in certain places and depress it in others. This is well shown along the

Atlantic coast of Canada, where the ancient shore line stands 575 feet above tide at St. Johns, Newfoundland, and declines to 250 feet in northern Labrador. The warping of the eastern part of the United States in the Appalachian region has resulted in the high mountains of North Carolina and the lower areas of Pennsylvania. Portions of Sweden are sinking while others are rising. Proofs of such movements are not to be seen in folds, since the rocks under these conditions are not compressed; but can be ascertained by careful measurements extending over many years, and especially by a study of elevated marine terraces and old land surfaces. The movement may be extremely slow, often being only a few inches a century.

Zones of Flow and Fracture. — The rock of the earth's crust is much fractured at and near the surface. Such fracturing, however, does not extend indefinitely downward, although at a depth of at least eleven miles[1] empty cavities may exist in granite, and if the cavities are filled with water, gas, or vapor, they may exist at even greater depths. It is evident, however, that at depths of even eleven miles many rocks less strong than granite will be unable to withstand the enormous weight of the overlying mass and will yield to the pressure, not by fracturing but by flowing, after the manner of wax. The portion of the crust which yields to pressure by fracturing and in which fractures consequently exist is called the *zone of fracture;* that portion of the crust below this, in which the rock yields by flowage, is called the *zone of flow.* In this zone cavities are absent and the particles of rock occupy the minimum space. Since rocks vary greatly in strength, it is evident that the depth to which the zone of fracture extends will vary with the rock, and that consequently the upper surface of the zone of flow is very irregular. Between the zone of flow and the zone of fracture is an intermediate zone in which the soft, incompetent beds flow, and the hard or competent beds fracture. This is called the *zone of flow and fracture.*

JOINTS

Attention has been called to the division planes or joints by which all rocks near the earth's surface are more or less broken into angular blocks (p. 25). This structure can be well studied in almost any quarry or cliff (Figs. 1, 5, 85). Joints approach

---

[1] Adams, F. D., — *An Experimental Contribution to the Question of the Depth of the Zone of Flow in the Earth's Crust:* Jour. Geol., Vol. 20, 1912, p. 97.

verticality in horizontal rocks, but are inclined at various angles in strata which have been folded. In horizontal strata it is usually found that two vertical systems of joints are present at right angles to each other (Fig. 1, p. 23), although more than two systems are often present. Two remarkable features of the joints of undisturbed, sedimentary rocks are (1) the horizontal extent of the joints which stretch many hundreds of feet in some cases, and (2) the smoothness of their faces. One often finds that the calcareous concretions and even the quartz pebbles contained in some beds are broken in two where joints cross them, with faces as smooth as if cut by a saw, and the faces of joints exposed in cliffs are often seen to be as smooth as a plastered wall. The distance between joints varies from a fraction of an inch to many yards.

Joints extend to considerable depths but cannot exist below the zone of fracture. They frequently end where a stratum of a different character is reached; for example, a joint which extends through a limestone may end where it reaches a shale. In such case other joints of a different interval may extend through the lower stratum.

Joints are taken advantage of in quarrying, but if they are very close together the blocks may be too small for building purposes, and if too far apart may make the profitable quarrying of the rock impossible. Some rich ore veins are developed in joints (p. 370).

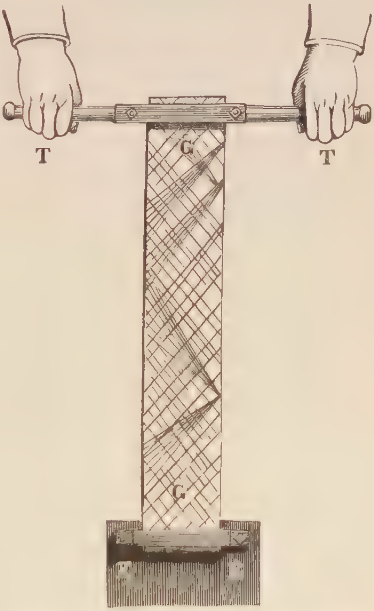


Fig. 250. — A plate of ice fractured by twisting movement, the cracks produced being chiefly nearly at right angles to each other. Some joints seem to have a similar origin. (After Daubrée.)

Origin of Joints. — The origin of joint planes in sedimentary rocks is not fully understood. It is generally believed, however, that they are the result of movements of the earth's crust and have been produced by powerful mechanical stresses and strains which are the result either (1) of torsion, or (2) of compression brought about by crustal movement. A suggestive experiment (Fig. 250), in which plates of ice and of other brittle substances were twisted by applying force at the two ends, produced cracks at right angles to each other, running diagonally from the corners.

The formation of columns in fine-grained, igneous rock is probably due to cooling and contraction, as has been explained (see also p. 333).

Effect of Joints on Topography. — The influence of joints in determining the courses of streams is especially noticeable in small streams. The brooks that flow into the lakes of central New York, for example, have their directions determined to an important degree by the systems of joints into which the strata are broken. The course of the Zambezi River in South Africa below Victoria Falls is a remarkable example of a large river which follows joints for a considerable distance. For many miles after it plunges over the fall the river is confined in a narrow gorge whose direction is a series of zigzags, this angular course being determined by the joints of the lava plateau in which the gorge is cut. The contours of coasts sometimes show the effect of jointing by the existence of angular bays and promontories (Fig. 251) where the rock is unequally jointed, permitting the waves to work faster in some portions than in others (p. 207). Joints also allow of more rapid work by weathering (p. 29), more rapid broadening of stream valleys (p. 88), the circulation of ground water, and the deepening of glacial valleys by plucking (p. 157). In limestone regions joints are often widened by solution and therefore have a marked effect on the topography of such districts.

FIG. 251. — A shore whose configuration has been greatly influenced by jointing. Holsteenborg, West Greenland. (After Hobbs.)

start

FAULTS

When beds are displaced along joints, bedding, or fracture planes, the beds are said to be *faulted* (Fig. 252). The fracture along which the movement occurred, usually is not an open crack. It sometimes consists of a single, clean-cut fracture, but more often of a number of closely parallel fractures. A fault dies out at its ends and varies along its course in the amount, direction, and character of the displacement. The fault line, moreover, is not always straight and single, but is often irregular and in many cases splits into one or more branches. Faults are seldom vertical, but when followed downward in mines are usually found to be inclined, the degree of inclination often varying from point to point. The general inclination of a fault from the vertical is called the *hade* (Fig. 252).

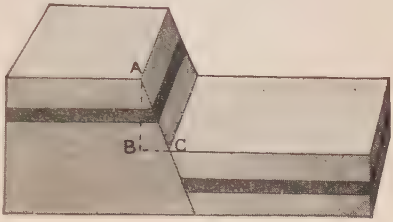


FIG. 252. — Normal fault. The horizontal displacement *BC* is the heave; the vertical displacement *AB* is the throw; the angle *BAC* is the hade; *AC* is the slip.

There are three principal types of faults: (1) *normal*, (2) *reverse* or *thrust*, and (3) *vertical*.

Normal or Gravity Faults. — A normal fault (Figs. 252, 253) is the simplest type. In faults of this class it is convenient to consider one side as having moved down an inclined fracture, and the other to have

FIG. 253. — Faults in sand, Adirondacks. Since the faulting, lateral movement has occurred and has changed the direction of the fault planes so that the footwall seems to be on the downthrow side.

remained stationary or to have moved up. The vertical displacement or the vertical distance between the ends of a dislocated stratum is called the *throw;* the horizontal displacement, the *heave.* The distance a stratum has moved on the *fault surface* is indicated by the term *slip.* The *upthrow* side is the one in which the beds lie at a higher level than their continuation on the opposite or *downthrow* side of the fault. These terms are used without reference to the actual direction of movement. The wall of the downthrow side is called the *hanging wall,* and the opposite wall, the *footwall.* These last two terms originated with miners, since in mining along a fault the overhanging side was naturally spoken of as the "hanging wall," while the side of the fault upon which they stood was called the "footwall." The fact that the hanging wall in normal faults has moved down relative to the footwall is utilized in coal mining. For example, if a seam of coal suddenly disappears at a fault, the fault plane is followed *down* or *up*, depending upon the inclination or *hade* of the fault surface (Fig. 254). Normal faults sometimes shade into monoclines (Fig. 248, p. 256).

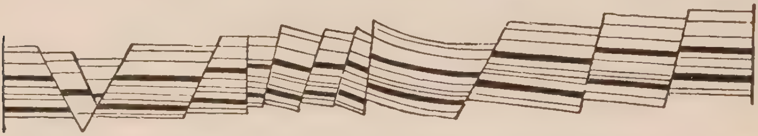


FIG. 254. — Section across Yarrow Colliery, England, illustrating the law of normal faults. The surface is restored. (After De la Beche.)

FIG. 255. — Mosaic of the rock floor of the Tonopah mining district, Nevada, produced by faulting. (After Hobbs.)

Examples of Normal Faults. — The earth's crust is more or less broken by faults; in some cases the faulting has taken place so widely and the various systems of faults extend in so many directions that a geological map of the region has the appearance of a mosaic (Fig. 255). The Colorado Plateau (Fig. 256) has been broken by normal faults, some of which can be followed for hundreds of miles and have a vertical displacement (throw) of several thousand feet. In traveling along the Mohawk valley between Albany and Little Falls one passes over nine easily recognized faults and probably over many smaller ones.

The term *graben* (Fig. 257) is used for a portion of the earth's crust bounded by faults, which is depressed relative to the surrounding masses, and the term *horst* for a section which is elevated relative to the surrounding masses and separated from them by faults. The Rhine valley, between Basle and Mainz, is an excellent example (Fig. 81, p. 100) of a graben. Here the valley is limited by parallel faults, the Black Forest lying on the east and the Vosges on the west. The valley occupied by the Jordan River and the Dead Sea of Palestine is a graben in which a fault block has sunk 2600 feet below the level of the plateau, depressing it in places below the level of the sea.

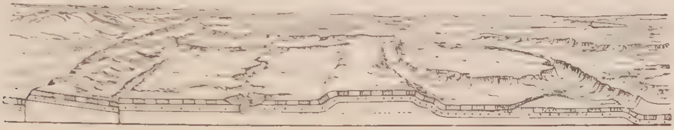


FIG. 256. — A section from east to west across the plateau north of the Grand Canyon, with a bird's-eye view of the surface. The effect on the topography of the great faults, folds, and monocline are well-shown. (Powell.)

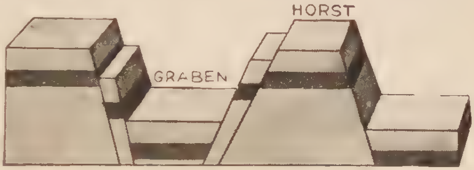


FIG. 257. — Block diagram showing the appearance and origin of a graben and horst.

Reverse or Thrust Faults. — In reverse faults the hanging wall should be considered as having moved *up*, and we thus find that instead of a stratum being separated as a result of the faulting, the two ends overlap so that the older beds are pushed over the

FIG. 258. — A fold passing into a thrust fault. (Heim.)

younger ones (Fig. 258 *C*). The result of thrust faulting in the Selkirks of Canada and in many other regions has been to move strata over and upon others that were formerly hundreds of feet higher. Occasionally, recumbent folds can be traced into thrust faults (Fig. 258 *A*, *B*). This is not surprising, since it is evident that both are due to lateral pressure; the movement being so great in the latter that the strain could not be relieved without breaking. Thrust or reverse faults involve a shortening of the earth's crust, as has been said, and differ in this respect from normal faults which are the result of a stretching of the crust. The fault plane usually approaches the horizontal more nearly in thrust faults than in normal faults; that is, the hade of the former is greater than that of the latter.

Examples of Thrust Faults. — Many examples of thrust faults might be cited. A great thrust fault (Bannock overthrust)[1] extends approximately 270 miles from northern Utah into Idaho, in which the older strata have slid over the younger (horizontal displacement) a distance of at least 12 miles. In the same region other faults with a throw of 15,000 to 20,000 feet have been described. In Massachusetts,[2] a thrust fault has been described in which the strata have slid along a fault surface for 15 miles. The southern Appalachian Mountains (Fig. 259) are broken by many faults that run parallel to the system. In Virginia and Georgia 15 or more parallel thrust faults occur, running from northeast to southwest, along which the older strata have been pushed over the younger. One of these faults has been traced for 375 miles, and its greatest horizontal displacement is at least 11 miles.

FIG. 259. — Thrust faults and folds in the southern Appalachians.

Vertical and Horizontal Faults. — If faulting has taken place along a vertical (90°) joint or other fracture, the arrangement of the strata may give the appearance at the surface of either a normal or a reverse fault, depending upon whether the right or left side moved down (Fig. 260). In many cases, along the same side of a given fault line the movement may have been upward in one place, downward in another, and without evident movement at another. In some cases, a fault occurs along bedding planes and is called a

---

[1] Richards and Mansfield, — Jour. Geol., Vol. 20, 1912, pp. 681–709.

[2] J. Barrell.

bedding fault. It should not be understood from the foregoing that the movement in faults is always merely up or down. Often the movement has both a vertical and a horizontal component, and occasionally the vertical movement is inconsiderable and the horizontal important. This was true of the fault that caused the San Francisco earthquake (p. 275), and it has been observed in mines, where the faulted surfaces can be studied, that evidences of horizontal movement are more often met with than those of vertical.

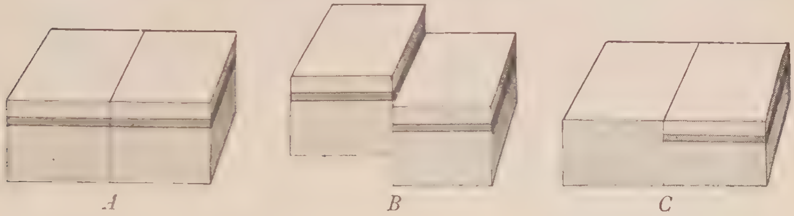


Fig. 260. — Diagrams showing *A*, horizontal strata; *B*, the strata displaced by a vertical fault; and *C*, the fault scarp obliterated by erosion.

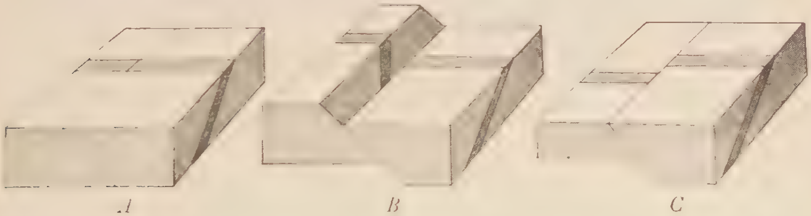


Fig. 261. — Diagram illustrating a dip fault and the effect of erosion upon the outcrop.

Influence of Faults on Topography. — If faulting did not take place long ago, it is evident that a cliff or *fault scarp* will be present, the

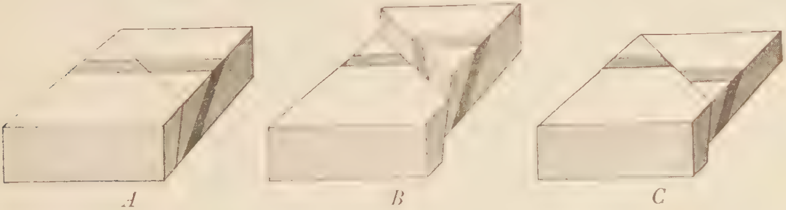


Fig. 262. — Diagrams showing the effect of an oblique fault upon dipping beds, and the outcropping of the stratum on the surface after the fault scarp had been planed by erosion.

height and prominence of which will depend upon the amount of the faulting and its recency (Figs. 261, 262, 263). Fault scarps are also formed when weak and resistant rocks are brought into contact by faulting. The weak beds are worn away more rapidly than the hard, so that after prolonged erosion the latter may form cliffs, even though they are on the downthrow side (Fig. 264). The original fault scarp is usually soon eroded to such an extent that the configuration of the land gives little or no indication of the existence of a fault. When, however, a resistant bed such as a sill (page 326) or a stratum of quartzite is present and is exposed by erosion, the fault will again be the indirect cause of a cliff (Fig. 264). In Scotland the relatively soft rocks of the central lowlands have been brought up against the relatively hard rocks of

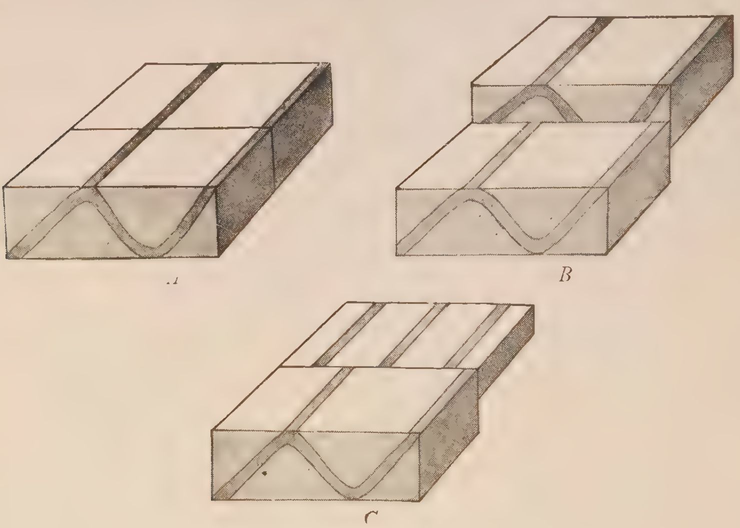


Fig. 263. — The effect of faulting on the outcrops of anticlinal and synclinal beds before and after the erosion of the fault scarp.

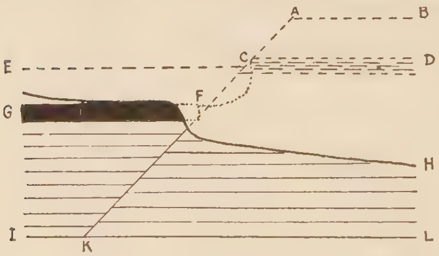


Fig. 264. — Diagram showing a cliff *BAC* formed by faulting. As erosion wore away the weaker rock a cliff resulted from the presence of the strong bed *CD*. Upon further erosion the bed *GF* appeared and the cliff *F* was formed.

the highlands, producing a strong line of demarcation (Fig. 265). Such a topographic form is called a *fault-line scarp* or cliff.

Sometimes the topography of a region is determined largely by faulting, resulting in steplike hills or mountains. This is well shown in a portion of Oregon (Fig. 266), in the Great Basin region of Utah (p. 354), the Colorado Plateau, and the Connecticut valley of Massachusetts and Connecticut. In central Sweden the crisscross valleys and lakes of angular and zigzag outline are, either directly or indirectly, due to the faulting of rhomboidal-shaped blocks. The greatest example of faulting now apparent in the topography of the continents is the Great Rift valley of east Africa, which consists of a series of grabens (p. 263) in the bottoms of which lakes (Albert, Tanganyika, etc.) are aligned. The magnitude of the displacement is indicated by the depth of Lake Tanganyika, which is nearly 4190 feet, the bottom of the lake lying 1600 feet below sea level. This great rift extends from Abyssinia southward for some 1500 miles. In the Adirondacks of New York the "latticed drainage" is to a

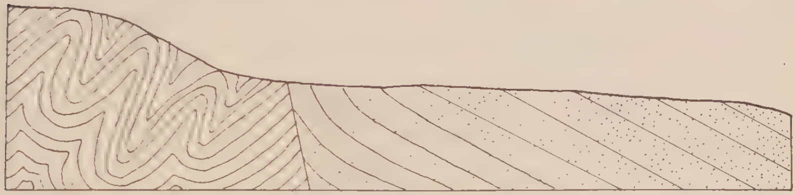


FIG. 265. — Fault in the Scottish Highlands. The strata on the right are weaker than those on the left.

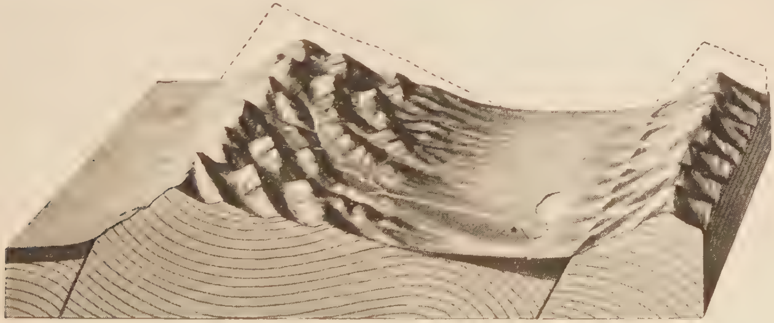


FIG. 266. — Diagram of a mountain formed by faulting. The slope of the surface of the original block is shown in outline. (Modified after Davis.)

great extent produced by faulting which caused the streams to flow in fault valleys.

Minor Features of a Fault Fracture. — When a fault fracture is visible, it is often found that it is represented by a zone of angular rock fragments, often cemented together to form a *fault* or *crush breccia* (Fig. 357), sometimes several yards wide. Some important gold and silver deposits occur in the filling of such breccia (p. 371). When the breccia is very resistant, as is the case when the filling is quartz, it may stand in relief after the surrounding strata are denuded, resembling a dike. The side of a fault surface is often polished and striated by the movement of the walls, so that it is possible to tell the direction of the movement from the striations. Such a surface is called a *slickenside* (Fig. 267). It resembles a glaciated surface but is usually more glazed.

Fig. 267. — A slickenside surface formed by lateral movement along a fault plane. The rock of one side of the fault was removed. (U. S. Geol. Surv.)

Detection of Faults. — Topography, as has been seen, is not always a safe guide for the detection of faults, since their presence is not always indicated by cliffs. The most satisfactory evidence of a fault is to be obtained when a geological map of a region is made, and it is found that all of the neighboring formations end upon a more or less straight line. A sudden change in the soil which is made apparent in the degree of fertility of neighboring fields, and the presence of rapids in streams which cross a fault are also indicative of the presence of a dislocation. Springs often occur along fault lines, and when a number of them are aligned they indicate, but do not prove

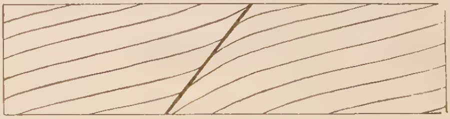


Fig. 268. — Diagram showing "drag dip" near a fault. (Modified after W. N. Rice.)

the presence of a fault. Dikes of lava also sometimes occur in fault fractures. In regions of horizontal rocks faults can often be traced along the surface some distance from the *fault line* (p. 277) by the upturned edges of the strata (drag dip), produced by the friction along the fault surface of the edges of the strata during the faulting (Fig. 268).

Origin of Faults. — In seeking an explanation for normal faults the fractures along which the movements occurred must first be found. These are often joints which, as has been seen, have probably been formed by tortional strains (p. 259). Normal faults indicate a stretched condition of the crust, which permitted the unequal settling of blocks bounded by joints or other fractures. In the formation of grabens and horsts (Fig. 257, p. 263) there appears to have been first a compression which arched the strata, followed by a relief of the pressure, which permitted the settling of the blocks of the arch. Reverse faults are evidently the result of lateral pressure and are best developed in highly folded and distorted rocks. Thrust faults often pass horizontally into folds, and vertically they sometimes shade gradually into more or less gentle folds (Fig. 269). The origin of the force which produced folding will be taken up more fully under the discussion of the formation of mountains.

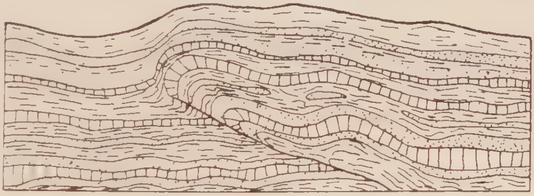


FIG. 269. — Diagram showing a fault shading into a fold. (After De Martonne.)

Rapidity of Fault Movements. — At irregular intervals dislocations of from a fraction of an inch to 20 or more feet have taken place in a few minutes along fault planes. In Owen's valley, California, in 1872, a slipping occurred along a line 40 miles long which resulted in a throw of from 5 to 20 feet. Along a fault 50 miles in length a displacement of as much as 30 feet occurred in Japan in 1891. Such faulting always produces earthquakes (p. 281). In some mines faulting is observed to be taking place continually, but at a slow rate. The total displacement resulting from such movements, if long-continued, will necessarily be great, but no surface features may mark its presence, since erosion may cut away the upthrow side as fast as it is formed.

Conformity and Unconformity

When strata are deposited one upon another in unbroken succession and without disturbance, they are said to be conformable (Fig. 1, p. 23). When, however, one set of beds is deposited on another which has been above the sea and there eroded, the two beds are said to be *unconformable*, and an unconformity, represented by the erosion surface which separates the strata, is said to exist. Unconformities may exist between stratified and igneous or metamorphic rocks (Fig. 322, p. 326). Usually, an unconformity is marked by some change in the relative dip of the beds, one set resting upon the upturned edges of an older series (Fig. 270). Such an unconformity is spoken of as an *angular unconformity*, because the strata below the unconformity meet those above it at an angle. An unconformity, however, sometimes occurs between strata which have not suffered any relative change in dip (Fig. 271); *i.e.*, both the younger and the older strata may be horizontal. In such cases the unconformity can usually be recognized by old erosion channels or by basal conglomerates (p. 240), but occasionally such a break is difficult to detect.

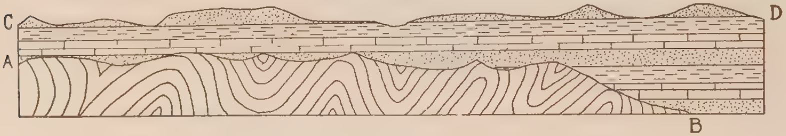


Fig. 270. — A diagram showing an unconformity or erosion interval, *AB*.

Fig. 271. — Diagram showing unconformities. The stratum *C* is separated from the strata *B* and *D* by unconformities. The unconformity between *B* and *C* is not readily noticeable, because the strata of both are horizontal. An unconformity exists also between the glacial drift *A* and the limestone *B*. (Near Milwaukee, Wisconsin.)

Importance of Unconformities. — Unconformities are of much importance in the study of the geology of a region, because of the geological history which they reveal. From the unconformity in Fig. 272 we learn (1) that there was a long period of quiet, during which the lower series of beds were deposited continuously on the ocean bottom. This was followed (2) by a period of folding or tilting and of elevation, so that these beds were raised above the level of the sea. (3) The strata were then subjected to erosion for such a long period that the upturned edges were worn to a peneplain. How long this *erosion interval* lasted cannot be told from any one geological section. (4) The land was later depressed and became sea bottom, so that (5) sediment was laid down on the old land surface. (6) Reëlevation again converted the sea bottom into land, and streams are now at work carrying the rock back to the sea.

FIG. 272. — An unconformity in which the lower beds are inclined, while the upper are horizontal. Wyoming. (U. S. Geol. Surv.)

Overlap is a term used in describing an unconformity in which the younger strata cover a larger area than the older ones and conse-

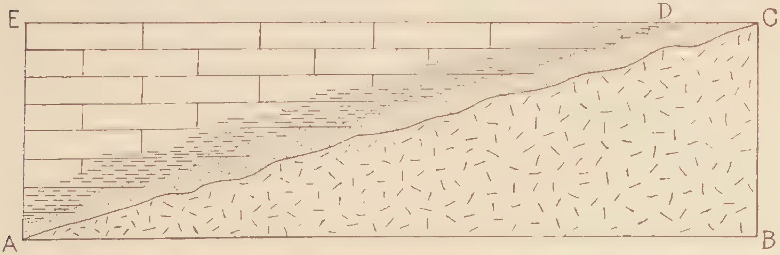


FIG. 273. — Diagram showing the overlapping of the strata *AEDC* due to the encroachment of the sea upon the ancient land surface *AC*. (Modified after Grabau.)

quently overlap the older strata (Fig. 273). They were deposited when the water in which they were laid down had a greater extent than it had when the older strata were deposited.

CONSTITUTION OF THE EARTH'S INTERIOR

The ancient Greeks and Romans in speculating about the underworld came to the conclusion that its heat and other igneous phenomena were due to the work of imprisoned giants. Our present theories are less fanciful, but because of the inaccessibility of the deeper portions of the earth's interior and our failure to reproduce the conditions there, our knowledge of its constitution is far from satisfactory.

Zone of Variable Temperature. — The temperature at the surface of the earth is variable because of the changes in daily and seasonal temperature, but at a depth which in Java and India is about 12 feet and in New York about 50 feet the temperature is constant throughout the year.

The Interior Heat of the Earth. — Below the level where seasonal change in temperature occurs, the temperature increases with the depth. This fact has been determined by well borings, by tunnels, and by mines, but since the deeper borings are only a little more than a mile in length, the statements in regard to the rate of increase at great depths must necessarily be theoretical. The rate of increase is usually estimated at 1° F. for 60 to 75 feet, but it varies so widely at different places that to strike an average is difficult. In the St. Gothard tunnel (Italy to Switzerland) it is 1° F. for 82 feet; at Calumet, Michigan, the average for 4939 feet is 1° F. for 103 feet; in the British Isles it varies from 1° F. for every 34 feet to 1° F. for every 130 feet. A boring in West Virginia to a depth of 5386 feet showed an increase of one degree for 80 or 90 feet for the upper half, and of one degree for 60 feet in the lower half. Near Leipzig, Germany, a boring 5560 feet deep showed an average of one degree for 56 feet. In South Dakota the artesian wells show a depth of from 17.5 to 45 feet for each degree. The rapid increase shown in South Dakota, however, is probably due to folding in the water-bearing stratum. The presence of hot igneous bodies would also increase the temperature gradient.

Since the temperature gradient follows the surface configuration, the level of the Simplon tunnel which connects Switzerland and

Italy was made higher than the grade of the railroad required in order that a too great temperature might be avoided, but even with this precaution the heat in some portions was so intense as almost to stop the work of excavation.

The heat of the interior of the earth is known also from lavas which reach the surface through volcanoes and fissures (p. 299). Copper wire, which melts at about 2200° F., has been fused when thrust into molten lava. In one case, where a lava stream from Vesuvius overflowed a village, brass was decomposed into its component metals. It is estimated that the initial temperature of lava, when it issues from Vesuvius, is probably more than 2000°.

Theories of the Physical State of the Earth's Interior

If the temperature of the earth increased uniformly from the surface downward at a rate of one degree for every 60 feet of descent, a temperature of 3000 degrees would be reached at a depth of about 34 miles. Such a temperature would be sufficient to melt all but the most infusible rocks *under the conditions existing at the surface of the earth*, but since the rocks at this depth are subjected to the enormous pressure of the overlying rocks, the conditions are very different.

(1). **Internal Fluidity Theory.** — Based on the assumption that the heat increases regularly from the surface downward, it has been held that the earth is a molten globe covered with a thin crust 25 to 30 miles thick. Although the belief in a molten interior has a wide popular acceptance, there are a number of serious objections to it.

(*a*) *Effect of Increasing Density.* — The rate of increase in temperature is probably not uniform, but diminishes with the depth. This is evident from the fact that the average specific gravity of the rocks of the earth's surface is about 2.8, while that of the earth as a whole is 5.5, so that the specific gravity of the central portion must be at least equal to iron, which is 7.7, and is probably higher. This increase in density is due to some extent at least to the great pressure of the overlying rocks, but may also be due to the concentration of heavy metals within the center of the earth. It has been suggested that metallic iron is to be found in greater quantity there than on the surface. But whatever the cause, the effect of increasing density would be to increase the conductivity of the rock, so that instead of a uniform increase of one degree for each 50 or 60 feet of descent, at a greater depth 70 feet might be required for a change of one degree, then 80 feet, then 100 feet, and so on. The increasing conductivity of the rock alone would, consequently, carry the temperature necessary to fuse rocks much deeper than 30 miles.

(*b*) *Effect of Pressure.* — Another serious objection to the theory of a molten interior is to be found in the effect of pressure on the melting point of rocks. Since nearly all substances expand upon melting, they remain solid when subjected to pressure which prevents expansion, and in order to melt them it is necessary to raise the temperature so high as to overcome the effect of the pressure. It is evident for this reason that it would be necessary to go deeper to find the fluid interior than if the pressure of the overlying rocks was slight. At a depth of 50 miles a temperature of 3500° F., though sufficient to melt almost any rock at the surface, might not be high enough to overcome the enormous weight of the overlying rocks, and since a still greater pressure is encountered at the increased depth necessary to obtain a higher temperature, it is evident that the melting point, for this cause alone, might never be reached.

(*c*) *Rigidity of the Earth.* — Two further objections to this theory have caused its abandonment by scientists. The first of these is that the earth is not pulled out of shape by the attraction of the moon and sun, as would be the case if it were substantially a molten globe. On the contrary it is shown to be more rigid than glass or steel. The second objection consists in the fact (Milne) that the velocity and character of earthquake waves (p. 283) suffer an abrupt change at a depth of about 30 miles, being transmitted at a more rapid rate below this level than in the crust, showing that the nucleus is more rigid than the overlying rocks.

(2) **Solid Interior.** — The second theory, as has already been indicated, is that the earth is substantially a solid because of the increasing conductivity and pressure.

(3) **Gaseous Center.** — Upon the assumption that below a depth of 190 miles the temperature of the earth is at the critical temperature of all substances (the temperature above which a substance can exist only in a gaseous state), it is held that the solid crust passes into a liquid zone, which in turn passes gradually to a gaseous magma. (Arrhenius.) The gaseous magma is potentially but not actually a fluid with a temperature above the fusion point of all substances. The rigidity of the earth, according to this theory, may nevertheless be greater rather than less than that of steel.

(4) **Radioactivity and a Solid Center.** — A fourth theory is in direct contradiction to the preceding and holds that the temperature of the interior is derived from the *heat given off by the radioactive minerals of the earth's crust.* According to this theory a radioactive crust, 30 to 45 miles thick, supplies all of the heat for the interior of the earth, and below a depth of about 45 miles the earth has a temperature of only about 1500° C. (Strutt.) So many elements of doubt enter into the above theory that it should merely be considered as suggestive, although all theories must take into account the enormous amount of heat generated in this way.

(5) **Subcrust Theory.** — Another theory which has been generally abandoned holds that between the solid crust and the solid center is a fused or semifused layer.

Summary. — Any hypothesis of the constitution of the earth's interior which is in accord with the known facts must hold (1) that the earth is a globe which increases in density from the surface toward the center; (2) that the temperature of the interior is intensely hot, perhaps 20,000° C. at the center, or even higher; (3) that the rigidity of the earth as a whole is greater than that of steel.

REFERENCES FOR STRUCTURE OF THE EARTH

Chamberlin and Salisbury, — *Geology*, Vol. I, 2d ed., pp. 486–589.
Geikie, J., — *Structural and Field Geology*, 3d ed., 1912.
Leith, C. K., — *Structural Geology*, 1913.
Reid, H. F., — Bull. Geol. Soc. America, Vol. 24, 1913, pp. 163, 186.

also ↑

CHAPTER VIII

study all of [illegible]

EARTHQUAKES

Earthquakes or tremblings of the earth's surface, when severe, are the most terrifying phenomena of nature, with the possible exception of violent volcanic eruptions. The tremblings of the earth vary greatly in their intensity, from those which cause great destruction of life and property to those which can be detected only by delicate instruments. Although severe earthquakes occur only at irregular intervals, specially constructed instruments called seismographs (Greek, *seismos*, earthquake, and *graphein*, to write) show that the earth is never free from minor vibrations. Such minor tremblings are produced by water waves, by changes in atmospheric pressure, by readjustments due to the lightening of the earth's surface by erosion and its weighting by sedimentation, by the strains produced by the attraction of the moon and sun, and in other ways. Destructive earthquakes are, however, of only occasional occurrence and arise from disturbances within the earth's crust (p. 281).

The San Francisco Earthquake. — The earthquake which in 1906 shook California and wrought such havoc in San Francisco was the most disastrous to property of any in North America within historic times, although the loss of life was slight. Much of the destruction, however, was due to the fires which were started as a result of the shocks, and to the breaking of the water mains of the city, which made it impossible to extinguish the flames.

The shock came without warning, as is usually true of great earthquakes, and lasted less than one minute. It was followed by others of less intensity during the day and for several weeks afterwards. Where the shock was severe trees were injured, — some being broken off, some overturned, and some split from the ground upward; buildings were shifted horizontally and often badly broken; animals were thrown from their feet and persons from their beds. It was found that the greatest intensity of the shock was along a fault line (p. 267), and that in general the violence diminished with distance from the fault on either side. "The rate of diminution, with the exceptions to be mentioned presently, may be expressed by saying that at five miles from the fault only a few men and animals were shaken from their feet, only a few wooden houses were moved from their foundations, about half the brick chimneys remained sound and in condition for use, sound trees were not broken, and no cracks were opened which did not immediately close. At a distance of twenty miles only an occasional chimney was overturned, the walls of some brick buildings were cracked, and wooden buildings escaped without injury; the ground was not cracked, landslides were rare, and not all sleepers were wakened. At seventy-five miles the shock was observed by nearly all persons awake at the time, but there were no destructive effects; and at two hundred miles it was perceived by only a few persons."[1] The exceptions to the gradual diminution of intensity occurred on the artificially filled or "made" land in the city, and where there were tracts of deep alluvial soil, especially where ground of this character was saturated with water (Fig. 274). Such ground behaved during the earthquake very much like "jelly in a bowl," the sudden shock causing it to be thrown into waves.

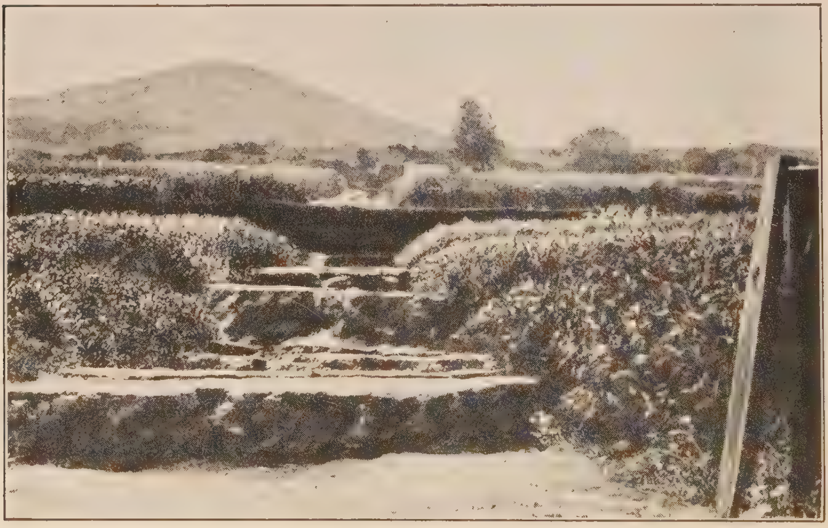


Fig. 274. — The slipping of alluvial soil toward the Salinas River, as a result of the San Francisco earthquake.

---

[1] G. K. Gilbert.

This earthquake was the result of shocks produced by renewed slipping along an old fault line which had been known to geologists for some time. The "earthquake topography" of such a fault line

FIG. 275. — Map of the fault line formed during the San Francisco earthquake in 1906. It was the vibrations set up by the faulting along this line that produced the earthquake. (U. S. Geol. Surv.)

is described on page 265. The fault line along which the slipping occurred has been traced about three hundred miles on the land (Fig. 275), and the principal movement was found to be horizontal

Fig. 276. — Fence parted by an earthquake fault, 1906. The fault fracture is inconspicuous, although the horizontal displacement is eight and a half feet. Near San Francisco. (U. S. Geol. Surv.)

instead of vertical (Figs. 276, 277) and to measure from 8 to 20 feet. Some vertical movement also occurred, but it was inconsiderable.

Distribution of Earthquakes. — A study of the distribution of earthquakes gives a clue to their cause. They occur (1) in volcanic regions, where the earth's crust is subjected to high temperature and to strains produced by explosions; (2) along belts of young and growing mountains, where strains are being relieved from time to time; (3) along coasts, where the sea bottom descends steeply from the shores, especially where they are bordered by high mountains. The conditions last mentioned are well illustrated in Japan, where the earthquake records since the beginning of the seventeenth century show that a severe shock has occurred on an average of once in two and a half years. By far the greater number of these have been accompanied by a movement along the scarp of the great Tuscarora Deep, which lies a short distance off the coast. (4) Earthquakes

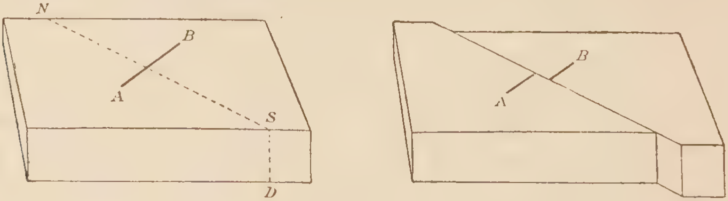


Fig. 277. — Diagrams illustrating the nature of the fault which produced the San Francisco earthquake. (After Gilbert.)

also occur where there has been an overloading with sediment. The great earthquake of the Mississippi Valley in 1811 may have been caused by a readjustment of the crust as a result of the great weight of sediment laid down there in recent geologic time. Boundaries were thrown into such confusion as a result of these shocks that it was necessary for the government to make a resurvey of 1,000,000 acres.

FIG. 278. — Earthquake regions of the Eastern Hemisphere, shown in black. (After Montessus de Ballore.)

The earthquake "danger spots" of the United States are situated on the Pacific coast, in the Great Basin (Utah), and in the lower Mississippi Valley. New England has been remarkably free from severe shocks, although many slight earthquakes have been recorded. In the last-named region the danger is greatest where lines of fracture intersect. Over the world as a whole two zones are recognized in which earthquakes are most frequent: the Mediterranean belt, which extends from Spain through the Himalayas to eastern China and from which 53 per cent. of the recorded earthquakes originated; and the Pacific belt, which borders the Pacific Ocean and from which 41 per cent. of the recorded earthquakes came. Only 6 per cent. of the recorded earthquakes have occurred outside of these two belts, showing how rare severe earthquakes are over the greater portion of the globe. The earthquake zones are shown in Figs. 278 and 279. It should not be concluded from the above that all parts of the earthquake belts are equally affected. For example, along the line of the proposed Nicaraguan interoceanic canal, earthquake shocks are frequent and severe, while along that of the Panama Canal they have been few and slight, as is shown by fragile arches which have remained standing for many years.

FIG. 279. — Earthquake regions of the Western Hemisphere, shown in black. (After Montessus de Ballore.)

Summary of the Causes of Earthquakes. — The earth may be caused to tremble in many ways. (1) Severe earthquakes have been produced by volcanic eruptions, but the disturbances thus caused are confined to comparatively small areas, as they are the result of steam explosions and of the fracturing of the rock as lava rises in the earth's crust.

(2) The falling of the roof of a cave may produce a jar which will cause some damage. The earthquake shocks at Visp, Switzerland, which fissured buildings and caused landslides, were due to the collapse of cavern and tunnel roofs, and the earthquakes which are of frequent occurrence in the Karst region (p. 72) on the east coast of the Adriatic are of this origin. The jar produced by the fall of an overhanging rock which formed the brink of a fall has been sufficient to break windows several hundred yards distant.

The above causes (1) and (2) are unimportant, and their effect is small.

(3) The great earthquakes of the world are a result of the fracturing of the rock of the earth's crust, or of the vibrations produced during faulting. (*a*) They may be due to the jolting of earth blocks whose movement begins and ends suddenly; and also when thick delta deposits suddenly slump an earthquake may be produced. (*b*) They are also due to the vibrations produced during faulting by the friction of one block as it rubs against another. This method may be illustrated by rubbing the closed fist on a table, or by rubbing two blocks of wood together. (*c*) They may be produced by a simple breaking of the rock. It has been suggested that some at least of such fracturing "may have relation to sudden deformation by rock flowage." (Leith.)[1]

It is evident from the above that great earthquakes are most likely to occur in growing regions; for example in young mountains, where the strains have not yet been relieved.

Displacements. — The amount of the movement of the earth along faults in the production of earthquakes varies greatly. After the California earthquake (1906) it was found, as already stated, that the movement was horizontal and varied from 8 to 20 feet. The movements of the crust in the Sumatra (East Indies) earthquake of 1892 were also horizontal, the total slip of the fault amounting to from 11 to 13 feet. No trace of the fault was visible at the surface, the proof of the movement being furnished by geodetic measurements. Vertical movements are perhaps more common than horizontal, although they are usually accompanied by some horizontal movement. The Japanese earthquake of 1891, for example, was produced by a fault which has been

---

[1] Leith, — *Structural Geology*, 1913, p. 69.

traced 40 miles, on one side of which the ground sank from 2 to 20 feet, while on the other side (the east) the wall of the fissure was moved 13 feet northward at the same time. The portion of the Alaskan coast affected by the earthquake of 1899 was found to have been displaced vertically in amounts varying from zero to 47 feet, the average being between 5 and 12 feet. The great earthquake of Owen's valley, California, in 1872, was produced by a fault which has been traced 40 miles, whose vertical displacement at the surface (throw) was from 5 to 20 feet. If a fault caused the Charleston earthquake (Fig. 280), no evidence of such movement appears at the surface.

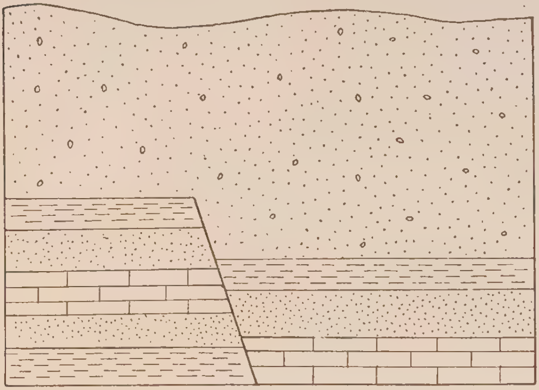


Fig. 280. — Diagram showing the absence of surface evidence of a fault, because of the presence of a thick, unconsolidated bed of sand above the solid rock.

It is sometimes found that the displacement along a fault not only varies in amount at different places, but also that along the same fault the downthrow side in one portion is on the right, for example, and at another on the left. Such a fault is called a *hinge fault.*

Many earthquakes originate beneath the sea, some of which have been very destructive. Off the coast of Greece the telegraphic cable broke at the moment of an earthquake in 1873, and upon subsequent examination it was found that the break was seven miles from land, and that the water which formerly had been 1400 feet deep at this spot was 2000 feet in depth after the shock. Submerged precipices 3000 to 5000 feet high occur in this region and are doubtless fault scarps whose formation caused many earthquakes. Many records are extant of vessels which were made to vibrate by submarine earthquakes, to such a degree that the crew thought that they had struck a reef; loose objects rattled about, and in some cases men were thrown to the deck by the violence of the shock.

Depth of the Plane or Point of Origin. — Wherever it has been possible to determine the direction of the emergence of the waves of great earthquakes, it has been found that they converge at a depth of less than 12 miles and usually less than 5 miles; that is within the zone of fracture. The point or place of origin is called the *focus.*

Earthquake Waves. — When the earth is shaken by an earthquake two sets of vibrations are started, one which follows the surface of the earth and another which passes through it, the former traveling more slowly than the latter, which passes through the 8000 miles of the diameter of the earth in about 17 minutes. Earthquake instruments (seismographs, p. 287) situated on the side of the earth opposite an earthquake shock show three series of vibrations: (1) preliminary tremblings, about 17 minutes after the shock, followed by (2) the strong vibrations of the principal shock, and finally by (3) a series of feeble vibrations (Fig. 281). Some of the waves are (1) compressive or longitudinal and have the same nature as the vibrations which travel through a liquid, and some are (2) transverse and vibrate at right angles to the direction of the transmission of the shock. Such waves as the latter can be propagated only in a solid.

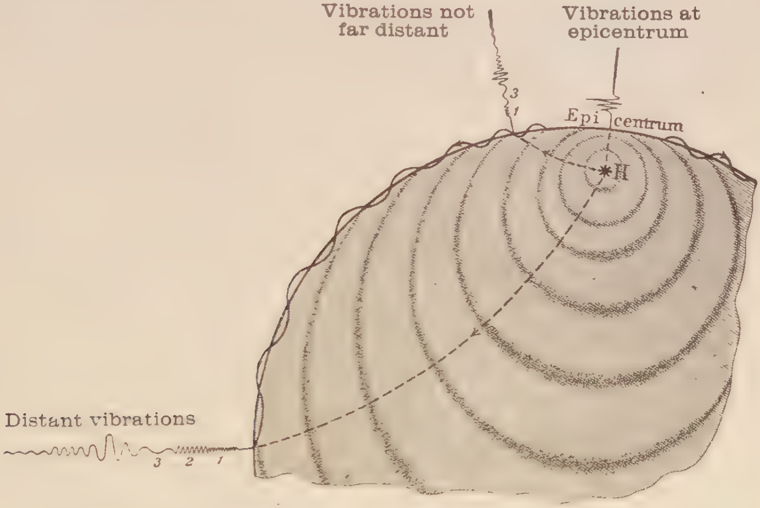


Fig. 281. — Diagram showing the path of earthquake waves and the vibrations which they produce. (After Sieberg.)

The velocity of the earthquake waves which pass *through* the earth is uniformly about 450 miles a minute, on the assumption that this movement is along a straight line. This indicates a rigidity of the earth's interior of one and a half times that of steel. The velocity of the *surface waves* varies with the rock through which they pass, and other conditions; that of the earthquake at Naples in 1857 being nine or 10 miles a minute, while in Germany in 1874 the rate was 28 miles a minute. The velocity depends to a large degree upon the density and elasticity of the rock, being much slower in sand and loose sandstone than in slate, schist, or granite. This has been shown experimentally by noting the velocity of shocks produced by explosions of gunpowder, and it has been found that the velocity is 825 feet a second in sand, and 1088 feet a second in slate and schist. In all such experiments, however, account must be taken of the presence of fissures and whether or not the fissures are filled with water.

Amplitude of Vibration. — By the *amplitude of vibration* is meant the distance each rock particle is moved from its position of rest during an earthquake (Fig. 282). It is a common notion that the amplitude is very great, but measurements show that they are minute, an amplitude of 20 millimeters (three fourths of an inch) being sufficient to destroy a city; one of 10 millimeters (three eighths of an inch) constituting a severe earthquake; and one of 5 or 6 millimeters being adequate to shatter a chimney. Amplitudes much greater than the above have been recorded. It should be remembered in this connection that it is the *suddenness of the shock* that makes it effective. This can best be illustrated by a simple experiment. If a stone or metal slab upon which a marble rests is struck a sharp blow, the marble will be thrown into the air, but it is evident that the actual movement of the particles composing the slab, and through which the vibrations were transmitted to the marble, was a very small fraction of an inch, the projection of the marble being due to the great suddenness of a small movement. This phenomenon is well illus-

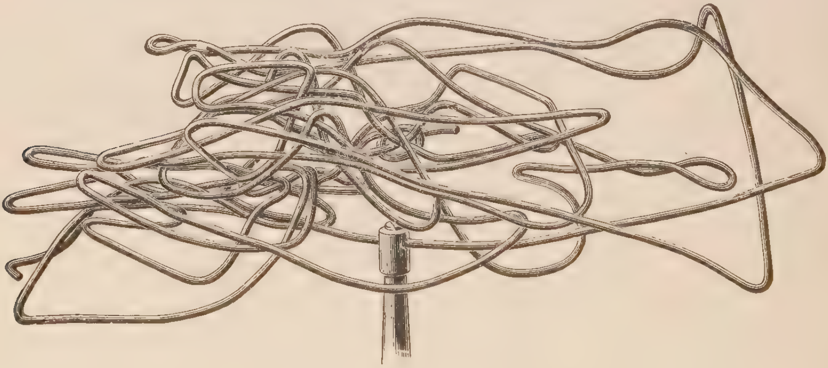


FIG. 282. — Wire model showing the motion of an earth particle during an earthquake. (Greatly enlarged.)

trated in some earthquakes. In one case (Calabria, Italy), the stonework of a well was thrown out of the ground, and in its new position resembled a small tower. In an Icelandic earthquake in 1896 persons lying on the ground near a cliff were thrown over the edge. More commonly stones are thrown into the air and overturned (Assam, India). Sometimes heavy objects such as gravestones are embedded more deeply in the ground (Fig. 283). The reason for this can be shown by another simple experiment. If a ball of soft clay upon which a pebble rests is subjected to a sudden upward movement, the pebble will be embedded, to some extent, in the clay.

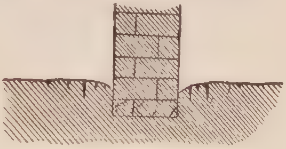


FIG. 283. — Pier driven into the ground by an earthquake shock.

The amplitude of the vibration of a rock particle should be distinguished from the earth waves which are produced in loose alluvium. For example, during the earthquake which shook the Mississippi Valley in 1811, and which was probably the most violent that has taken place in North America since its settlement by Europeans (although not the most destructive because of the sparseness of the population and the character of the buildings), the ground is described as having been thrown into great waves, so that the branches of the trees interlocked as the waves passed under them. In this case, the amplitude of the vibrations of the rock upon which the thick alluvial soil rested probably did not exceed a few millimeters.

Vorticose and Twisting Movements. — After earthquakes, pictures are often found with their faces toward the wall, furniture has been turned partly or completely around, statues have been twisted on their pedestals and chimneys have been partly turned about. No one cause can be assigned to such movements. In many cases the turning was due to a simple motion backward and forward; in others the rotation probably resulted from "a combination of shocks from separate faults." (Hobbs.) The latter is given as the cause of the turning of a bronze angel in Belluno, Italy, through an angle of 20°, and the rotation of the statue of Queen Victoria in Kingston, Jamaica.

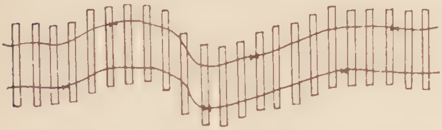


FIG. 284. — Diagram showing a railroad track bent during the Charleston earthquake.

The bending of railroad tracks (Fig. 284) and the zigzag position of rows of trees which were straight before the earthquake were produced by the lateral shifting of earth blocks.

Duration. — The duration of a severe earthquake is very short. As has been stated, the shock which destroyed San Francisco lasted about one minute, and the movement along the 300 to 400 miles of fault rift probably did not consume two minutes. The great Assam (India) earthquake lasted only two and a half minutes, and the destruction was accomplished during the first 15 seconds. The destructive shocks of the Charleston earthquake lasted a little more than half a minute. Between December 16, 1811, and March 16, 1812, at least 1874 shocks were felt in the Mississippi Valley, of which eight were severe. No individual shock, however, was of long duration.

Frequency. —Delicate instruments (seismographs) show that the earth is continually trembling in all parts, and it is probable that quakes severe enough to be felt are shaking the earth in some regions at all times. Certain portions of the world as, for example, parts of Japan and southern Italy are subject to frequent shocks. In the former, a severe earthquake occurs on an average of every two and a half years, and minor shocks four times a day. A careful record of the aftershocks of the earthquake at Messina, Sicily, in 1908, shows that 87 shocks were felt during the first four days and 862 during the following year, four of which were severe.

All definite predictions as to the time and place of earthquakes are of little value. This is illustrated in the case of San Francisco. The earthquake rift or fault line was known before the earthquake. It was believed that renewed faulting might occur at any time, but whether within one year or many years could not be foretold. Since earthquakes are the result of a relief of strain, it is evident that a region is *likely* to be immune from severe shocks for some years after it has been shaken, since the strains which produced the shock have been partly or entirely relieved, and a shock will not occur until strains have again accumulated.

Areas Affected by Certain Earthquakes. — The areas affected by earthquakes vary greatly in size. A region four times the size of Europe is said to have been affected by the Lisbon (Portugal) earthquake of 1755; that shaken by the great Assam (India) earthquake of 1897 was 1,750,000 square miles, of which 150,000 were laid in ruins. An earthquake in 1891 shook three fifths of the entire area of Japan.

The Charleston (South Carolina) earthquake affected an area 1000 miles in diameter.

Instruments for Determining and Measuring Earthquakes. — Earthquake instruments or seismographs have been established in many parts of the world, and from them the location and intensity of earthquakes are known. For example, seismographic records will be made in Germany, the United States, and elsewhere of an earthquake in Java or the West Indies. Seismographs vary widely in construction, but since they all endeavor to show the direction of the vibrations, the essential feature consists of three pendulums arranged so as to vibrate in mutually perpendicular directions, the record being made on a sheet of paper which moves at a uniform rate (Fig. 281).[1]

Effects of Earthquakes

Faults and Fissures. — We have seen that earthquakes are usually the result of faulting. Sometimes the fault rift extends to the surface as an open fissure, but more often the fissure is closed. When deep alluvial soil is shaken, many cracks are often formed, as a result of the compacting of the loose material and of its slumping. Such fissures are especially likely to form in stream valleys parallel to their course (Fig. 285), since the alluvium is unsupported on the stream side and moves in that direction, if at all. As a result of such slumping cracks are formed and valleys are narrowed. Fissures formed during the Mississippi Valley earthquake of 1811–1812 are still visible. One such fissure diverted the course of the Mississippi River so that an oxbow (p. 121) was cut off.

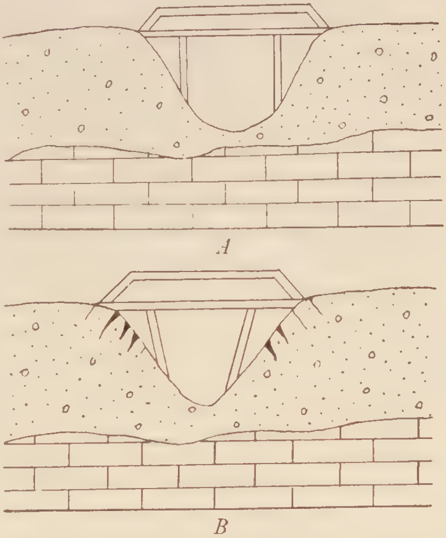


Fig. 285. — Diagrams showing the effect of earthquake shocks upon loose material. The bridge girder has remained in place, but the piers have moved inward at the bottom.

---

[1] For a more complete description of seismographs see: Hobbs, *Earthquakes* pp. 257–275.

In Arizona the waters of several streams now flow into a fissure formed during an earthquake (Fig. 286). In some earthquakes fissures have opened and then closed again, entrapping people and animals, and engulfing houses.

FIG. 286. — Fissure produced at the time of an earthquake. Arizona. (U. S. Geol. Surv.)

Changes in Level. — It is usual to find that the level of the land has changed during earthquakes. As a result of the earthquake of 1811–1812 in the Mississippi Valley, Reelfoot Lake, 25 miles long and 5 miles wide, was formed, the trees still being visible on its bottom. In the same earthquake Lake Eulalie was drained. In the Indian earthquake of 1819, a lake about the same size as Reelfoot Lake was formed. There is also often a lateral shifting of the ground during an earthquake, as in that at San Francisco, which moves the plains or mountains in one direction on one side and those on the opposite side in the opposite direction (p. 278). The changes of level on opposite sides of faults which produce falls and lakes have already been discussed (p. 262) (Fig. 287); elevation is as frequent an accompaniment of earthquakes as depression. During the earthquake which shook lower India in 1819, an area 50 miles long and 10 miles broad was elevated 10 feet and is called the Mount of God. Over an area of 600,000 square miles the coast line of Chile and Patagonia is said to have been elevated during an earthquake in 1835.

Landslides. — One of the most obvious effects of a severe shaking of the earth is the production of landslides and the slumping of thick soil which rested on a slope. The hills about Kingston, Jamaica, for example, are scarred by landslides formed during the earthquake of 1907. As a result of an earthquake in India in 1897, the hills were stripped of their forests by landslides. This permitted erosion to proceed so rapidly as to overload the streams, with the result that the rivers, instead of flowing from deep pools over rapids, flowed in broad, shallow channels over a sandy floor. An earthquake in Greece in 1870 caused great landslides which dammed up some of the valleys and formed lakes, some of which are still in existence.

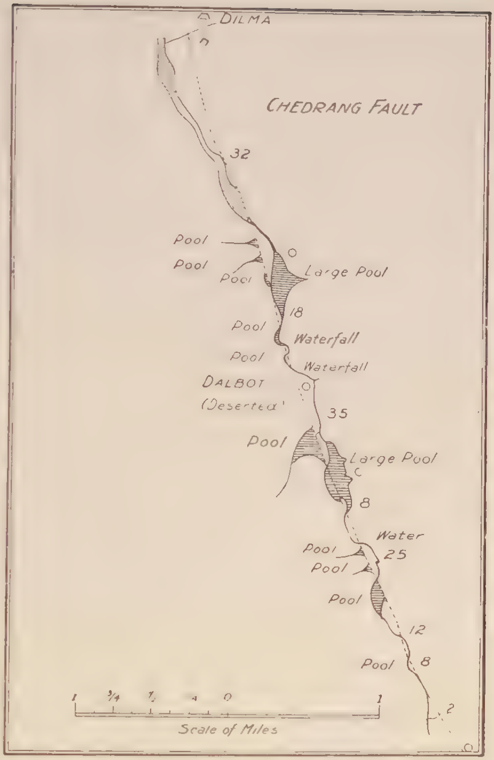


FIG. 287. — Map of the Chedrang fault, India, showing the effect of faulting on drainage. The figures show the amount of vertical elevation in feet. The river in places flows along the downthrow side of the fault, and is ponded back in others. The tributary streams also are dammed, forming pools. Waterfalls are formed where the river crosses the fault. In one place the fault runs along the old and now dry bed of the river, while the stream itself flows in a depression on the downthrow side. The large pools are not formed by the fault scarp, but by the reversal of the original slope of the river bed by the unequal elevation of the land, there being no elevation at the pools, but an elevation of more than 30 feet above each pool, and a lesser elevation below. (After Oldham.)

Earthquake Topography. — A description of the fault rift along which occurred the movement which produced the San Francisco earthquake will serve, in a general way, for all such earthquake faults or earthquake topography. This line is well marked for a distance of 43 miles and follows a system of long, narrow valleys, except where it traverses wide valleys for short distances. In some places it passes over mountain ridges, sometimes by a pass, but in some cases over the shoulder of a mountain. Along the fault line low, precipitous cliffs or *scarps* occur. Small basins or ponds, many having no outlet, are of fairly frequent occurrence and usually lie at the base of the scarps. Trough-like depressions bounded on both sides by scarps also occur, and are due to the subsidence of the ground or to an uplift on one or both sides. In the Japanese earthquake of 1891 the fault line showed itself in some places as a ridge, as if made by a gigantic mole just beneath the surface (Fig. 288).

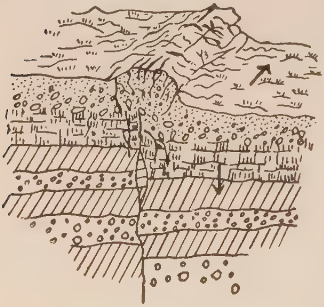


FIG. 288. — Diagram showing a ridge formed above a fault plane. (After Hobbs.)

Sounds. — Accompanying or slightly preceding earthquakes, sounds, described as a hollow rumbling or grinding and sometimes as a roar, have often been noticed. These are produced by the breaking and grinding of the rock as it is thrown into vibrations, and by the falling and breaking of objects on the earth.

Loss of Life. — The destruction of life is more impressive than any other effect of an earthquake. In 1812 Caracas, Venezuela, was so severely shaken that 10,000 people were killed, while the loss of life in Lisbon in 1755 amounted to 30,000. In 1905 an earthquake in India (Kangra) destroyed 20,000 people, and it is estimated that in 526 A.D. between 100,000 and 200,000 were killed by the shocks which devastated the shores of the Mediterranean. In 1908 the Messina earthquake, described as the world's most cruel earthquake, destroyed 77,283 people; and more than 30,000 were killed in the Italian earthquake of 1915.

Fish in great numbers are sometimes killed by earthquake shocks which affect the sea, lakes, or rivers.

Effect on Underground Water. — After severe earthquakes it is not unusual to find that some springs have become dry, that some have had their volumes increased or decreased, and that some have burst forth where none formerly existed. Along a fault rift which extends for 120 miles in Afghanistan and Beluchistan over mountain and valley, springs are found in abundance, the volumes of which are said to be augmented after an earthquake disturbance. So marked is this rift that it has long been utilized as a thoroughfare. The composition and temperature of the water of springs is also sometimes changed as a result of an earthquake shock. It is evident that the cause of this disarrangement of the underground water is the opening and closing of fissures leading to water-bearing strata or joints, and to faulting which may open a water-bearing stratum to a fissure.

FIG. 289. — Craterlet formed during the Charleston earthquake. (U. S. Geol. Surv.)

It is not unusual to find sand or mud cones and "craterlets" after earthquake shocks (Fig. 289). These are formed by jets of water which were forced through fissures during the disturbance. The water forming these jets originated in a water-bearing stratum or in water-bearing strata, or in fissures and caverns.

Gases. — Gases, usually containing large amounts of sulphureted hydrogen (H_2S), are also sometimes discharged, with or without water. These gases were imprisoned in the soil and escaped either as a result of the fissuring of the ground or by being forced out by the shaking together of the loose material. The sulphureted hydrogen was doubtless formed, for the most part, by the decomposition of animal and vegetable matter in the soil, just as is that which rises from the mud on the bottom of ponds when it is stirred with a stick. The escape of the sulphureted hydrogen was especially noticeable in the Mississippi Valley and Charleston earthquakes.

Construction of Buildings in Earthquake Regions. — A study of the effects of earthquakes on buildings has led to certain recommendations concerning the location and construction of houses in earthquake regions. (1) Artificially filled ground and deep alluvial soils should be avoided, since these are likely to be badly fissured and are, moreover, thrown into large waves by a shock. (2) A firm and stable foundation is of paramount importance, and particularly on soft and " made " ground. (3) Low structures, especially when well braced, with the beams and rafters attached firmly to the walls, are most desirable, because if a building does not vibrate *as a whole*, the parts act as battering-rams to throw over or break the walls. (4) Since the fires which almost invariably accompany earthquakes are often more destructive than the earthquakes themselves, it is important that there should be ample fire protection. It is estimated that had the buildings at Messina been properly constructed at the time of the earthquake in 1908, 998 deaths out of every thousand would have been prevented.

Effect of Earthquakes on the Sea. — One of the most disastrous effects of earthquakes on low coasts is produced by the *great sea waves* (tsunamis) which sometimes follow the shocks. After the first severe trembling which shook Lisbon in 1755, the sea retreated from the shore, laying bare the bottom of the harbor, and then returned in a wave 60 feet high which completed the devastation of the city. This wave was destructive along the coasts of Portugal and Spain and was felt on the coasts of countries far distant. A great sea wave cost the lives of 27,000 people in Japan in 1896.

The velocity of great sea waves and the distance to which they are propagated is well-known. In the Japanese earthquake of 1896 the wave which reached Honolulu, 3500 miles away, was 8 feet high at that place, and its mean velocity between these points was 681 feet a second. It was also recorded at San Francisco, to which point its mean velocity was 664 feet a second. The great sea wave from an earthquake in Peru, South America, in 1868, reached Honolulu, 5500 miles away, in 12 hours, and Japan, over 10,000 miles away, the next day. Because of their great wave length (sometimes 200 miles), great sea waves may not be sensible to vessels in mid-ocean and are never destructive until they reach a shallowing shore.

Great sea waves are apparently not all due to the same cause. Some are probably produced by a sudden depression of a portion of the ocean bottom by faulting and a consequent drawing in of the ocean water. This causes the withdrawal of the water from the land, and the wave set in motion by the meeting of the water then spreads in all directions, devastating low-lying coasts. A sudden shock on the sea bottom is probably also competent to give rise to a great sea wave. Explosions of submarine volcanoes set waves in motion which may work great havoc on low coasts.

Evidence that a Region has been Free from Severe Earthquakes. — It is not always possible to tell whether or not a region has been subjected to earthquakes; but some features such as pinnacled rocks with insecure bases and steep hillsides covered with soil give evidence that a region has been free from violent shocks for many centuries. For example, New England has probably been free from devastating earthquakes since glacial times, as the almost precipitous, soil-covered slopes of many hills and mountains show. This is also borne out by the occurrence of perched bowlders in very insecure positions.

REFERENCES FOR EARTHQUAKES

Davison, Chas., — *A Manual of Seismology*, 1921.

Dutton, C. E., — *Earthquakes in the Light of the New Seismology*, 1904.

Fuller, M. L., — *Our Greatest Earthquake:* Pop. Sci. Monthly, Vol. 69, 1906, pp. 76–86.

Geikie, A., — *Textbook of Geology*, Vol. 1, 4th ed., pp. 358–377.

Gilbert, G. K., — *The Investigation of the San Francisco Earthquake:* Pop. Sci. Monthly, Vol. 69, pp. 97–115.

Hobbs, W. H., — *Earthquakes, an Introduction to Seismic Geology*, 1907.

Lawson, A. C., *et al.*, — *The California Earthquake of April 18, 1906:* Report of the State Earthquake Investigation Commission, Carnegie Institution of Washington.

Tarr, R. S., and Martin, L., — *Recent Changes of Level in the Yakutat Bay Region, Alaska:* Bull. Geol. Soc. America, Vol. 17, 1906, pp. 29–64.

Wright, C. W., — *The World's Most Cruel Earthquake:* Nat. Geog. Mag., Vol. 20, 1909, pp. 373–396.

Carnegie Institution Publication 87, Vol. 1, Plate 15 and Atlas.

Seismological Journal. Many excellent articles.

CHAPTER IX

VOLCANOES AND IGNEOUS INTRUSIONS

A VOLCANO may be regarded as an opening in the earth's surface through which various gases and solid or molten rocks are ejected. The materials brought to the surface accumulate around the opening, forming a conical hill or mountain. The rapidity with which volcanic cones are built up is in contrast to the slowness with which other elevations are formed (p. 362), and they are able, consequently, to defy the agents of erosion during the period of rapid growth. Volcanoes are, moreover, capable of destroying in a very short time reliefs which erosion would be able to wear down only after centuries of work; as, for example, when one destroys a large part of its cone in a few hours. However, although conspicuous, the work of volcanism, because of its limited extent is unimportant as compared, on the one hand with the movements which are raising the earth's surface, and on the other with erosion, which is lowering it and is universal in its effects.

How Volcanoes Begin. — The first step in the development of a volcano is the opening of a passage to the surface. This opening may be caused by the "blowing out" of a portion of the earth's crust with the resulting formation of a funnel. More usually, however, it is a fissure through which gases, ash, and lava are ejected. The opening through which the material is ejected is usually enlarged by explosive action or by melting, and the lava and other ejectamenta tend to form a ring as they fall back to earth, until a hill is built up with a depression or *crater* in the summit. It is apparent, therefore, that the cone is not an essential part of a volcano, but is secondary to the vent, being merely a result of its action, not a cause.

New Volcanoes. — It is not often that man has seen the birth of a volcano, but a few well-known instances may be mentioned. On the shore of the Bay of Naples, amidst gardens and cottages, a volcano called Monte Nuovo had its birth in 1538, and in the course of two days built a cone to a height of about 500 feet. The eruption lasted only a week and has not been renewed since. An examination of the material of the cone showed that most of it was of volcanic rock, but that pieces of Roman pottery, fragments of the surface rock, and marine shells were also present.

On a plain in Mexico between 2000 and 3000 feet above the sea, covered with fields of sugar and indigo, a fissure opened in 1759, from which rocks were thrown to great heights and about which several cones were built up, the smallest to a height of 300 feet and the largest, Jorullo, to that of 1300 feet above the plain. The eruption, which began in June, 1759, ceased in February of the following year.

Volcanic cones have also been built up from the ocean bottom within recent times. In 1811 one such (Sabrina) was formed off the Azores, rising to a height of 300 feet above the sea. As it was composed of ash, it was soon washed away by the waves. Many of the great volcanoes of the world, such as Vesuvius, Etna, and Mauna Loa, began as submarine volcanoes many thousands of years ago and built up cones from abyssal depths.

Classification of Volcanoes. — Volcanoes are usually classified as active, dormant, and extinct. This classification is unsatisfactory, since a volcano which has long been considered to be extinct may become suddenly active, and volcanoes classed as dormant may never again be in eruption. For example, Vesuvius must have been regarded as extinct at the beginning of the Christian era, since it had been inactive so long that its crater was covered with vegetation, yet in a few days in the year 79 one half of its crater was blown off by a series of powerful explosions, and it has been intermittently active ever since. Volcanoes which have not been in eruption during historic times are said to be extinct; those which have been active in modern times, but are now inactive, are said to be dormant. All volcanoes may become active after a period of quiet, or may become extinct after a single paroxysm; such, for example, as that of Monte Nuovo.

MATERIALS ERUPTED

The materials brought to the surface by volcanoes may be classified as gases, solid matter, and lava flows.

Gases. — The difficulty in collecting gases from the crater of a volcano during eruptions renders our knowledge of them rather incomplete. In fact, whatever information we have has been largely obtained from *fumaroles* or openings on the flanks of the volcano from which fumes issue, and from the crater after eruptions have ceased.

The principal gases given off during volcanic eruptions are sulphureted hydrogen (H_2S), sulphur dioxide (SO_2), carbon dioxide (CO_2), carbon monoxide (CO), hydrochloric acid (HCl), hydrogen (H), oxygen (O), nitrogen (N), argon (A), and water. It is stated that the gases emitted from Vesuvius in 1906 contained so much ammonia and hydrochloric acid that the glowing lavas were shrouded in a veil of ammonium chloride (NH_4Cl) vapor, and that the "pine tree" cloud of yellowish "smoke" which hangs over that volcano during eruptions consists chiefly of ammonia compounds. The glare of the red-hot lava in the crater is reflected from this cloud and gives the appearance of a burning mountain.

The composition of the vapors depends upon the state of activity of the volcano; chlorine is more abundant in the energetic phases, while sulphurous and carbonic gases characterize the dying out of activity.

According to recent investigations, steam seems to be in smaller quantities than formerly thought. This contention is supported by the facts (1) that the amount of steam in craters decreases as the center of the crater is approached; (2) that the white cloud which hangs over volcanoes during eruptions is a mixture of solids and gases, and not steam as it appears; (3) that volcanic ash is invariably white and consequently has the appearance of steam when in suspension in the air; (4) that the volcanic cloud never produces rainbows or aureoles.

The great quantity of steam rising from some parasitic cones and from some lavas, however, is enormous. For example, it has been estimated that from one of the many parasitic cones of Etna sufficient steam was ejected during one period of one hundred days to form, if condensed, 462,000,000 gallons of water. The steam of fumaroles is, however, apparently largely of *surface origin*, as is shown by the increase in quantity after rains.

Fragmental Materials. — All of the substances thrown into the air by volcanic explosions, which fall to the ground in a solid state, are included under the term *fragmental materials*, and are classified as (1) dust, (2) ash, (3) cinders, (4) bombs, and (5) blocks of rock. These solid ejections are either portions of the rock which has been broken into pieces by the force of the explosions, or lava which was hurled into the air in a liquid condition but which solidified before reaching the ground. The size of the fragments varies from rocks weighing many tons to the finest dust, which may remain in the air many months. The term *ash* applied to this fine material is misleading, since dust and ash are not the result of combustion, as the name seems to imply, but of the shattering of the rock or lava by explosions, the pulverization of lava by sudden cooling after it is hurled into the air, and the collisions between stones as they are hurled from the crater or as they fall back to the ground. No part of the work of volcanoes has a greater geological importance than the production of dust. Some of it is so fine that no watchcase is so closely fitted as to prevent its entrance. Near the vents it is sometimes scores of feet thick, and in regions several hundred miles away it is sometimes deposited to a depth of several inches. For example, in 1783 the dust from an Icelandic volcano was carried to Scotland, a distance of 600 miles, in sufficient quantity to destroy the crops.

The larger particles are termed *cinders* and often constitute the conspicuous deposits of the volcanic cone, the fine dust having been carried away by the wind.

When a mass of molten lava is thrown into the air, it takes a more or less globular form and is called a *bomb*. Two kinds of bombs are common: one spindle or almond-shaped (Fig. 290), with an exterior only slightly cracked; the other with a surface cracked and broken, like that of the crust of a loaf of bread. The cause of the difference is to be found in the degree of liquidity of the lava. The spindle-shaped bombs were formed from very liquid lava, and their shape was produced by their gyratory motion in the air, while the "bread-crust" bomb was formed from viscous lava which was little affected by the rotation, and which cracked in cooling, forming a glassy surface and a porous interior. Bombs vary in size from a few inches to several feet in diameter.

FIG. 290. — Volcanic bomb, Aukland. The elliptical form is acquired as fragments of rapidly rotating liquid lava are cooled as they pass through the air. (After Marshall.)

When the ejected lava is blown full of holes by the expansion of the gas which it contains, it becomes so cellular that it is practically rock froth, the air cavities being sometimes eight or nine times greater than the inclosing glass, so that it is light enough to float upon the water. When it is in this condition, it is called *pumice*. After the eruptions of certain volcanoes situated on shores, great quantities of floating pumice have covered the neighboring waters so thickly as to be a menace to navigation. During the eruption of a volcano in Japan so much pumiceous material was thrown out that it was possible to walk a distance of twenty-three miles upon the débris floating on the sea.

The size of the blocks of rock thrown out during eruptions varies greatly with different volcanoes. A 200-ton block was hurled a distance of nine miles by Cotopaxi, and a rock fragment 100 feet in diameter was ejected from the Japanese volcano Asama.

The quantity of fragmental material ejected by volcanoes can best be shown by a few examples. It has been estimated that 4.3 cubic miles of material were ejected from Krakatao (p. 304) in 1883, and 28.6 cubic miles from Timboro in 1815. During the eruption of Sumbawa in the same year an area of nearly 1,000,000 square miles was covered by an amount of fragmental material estimated to be sufficient to make 185 mountains of the size of Vesuvius.

Lava. — All molten rocks which issue from the earth and also the solid rock which results when they cool are included in the term *lava.* The term *magma* is applied to the igneous fluids of the earth's interior, whether they give rise to volcanic activity or are intruded below the surface. Lava streams issue either from the crater of a volcano by overflowing or breaking through its rim; from fissures or openings on its flanks; or through fissures in the earth's surface (Fig. 291), where there are no volcanic cones. When they issue from a volcano they flow down the steepest slope; when they reach a gentle slope they spread out; when some obstacle, such as a stone wall, is encountered, their progress is at first stopped, then they either overflow or overthrow it, or pass around its ends.

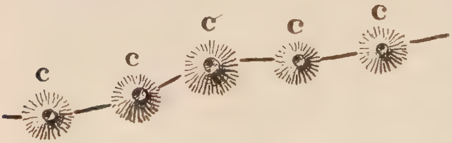


Fig. 291. — Small craters, *c*, *c*, *c*, along a fissure, through which lava has been extruded.

Lava Streams. — The surface of a lava stream, which at first glows like red-hot metal, cools quickly and blackens, but since the heat of the interior is kept in by the porous crust thus formed the deeper parts of the stream remain in a molten condition for a long time, occasionally for several years. One can often walk across a lava flow a few days after it ceases to move, and while the deeper portions are still molten, without suffering any inconvenience. After the crust has hardened, the still molten lava of the interior may continue to flow until it drains out, leaving a tunnel which may be several miles long (p. 309). A lava tunnel on Mt. Shasta, California, which is 60 to 80 feet high and 20 to 70 feet broad, has been explored nearly a mile without its end being reached.

Effect of Composition on Fluidity. — Lava varies greatly in composition and fluidity. Some lava streams have flowed 20 to 30 miles or more, while others have solidified as soon as they issued from their craters; some have flowed several miles, while others, with an equally high temperature and even greater volume, have moved a much shorter distance on an equal slope. This difference in the fluidity of lavas is due largely to their chemical composition and to their temperature. The basic, dark-colored lavas (p. 329) fuse at a lower temperature and are consequently more likely to flow long distances. The acid, usually light-colored lavas (p. 329) melt at a higher temperature and consequently become solid while still hot. They are therefore likely to solidify quickly. It is evident, however, that if a basic lava has a temperature which is but slightly above the melting point, it will be as stiff (viscous) as an acid lava at a high temperature.

Temperature. — The temperature of lava when it issues from the vent of a volcano is probably often greater than 2000° F. This is shown by the fact that copper wire, whose melting point is 2200°, was fused in a Vesuvian lava stream which had already lost some of its heat (p. 273). The temperature of the lavas in Kilauea in July, 1911, was 1260° C. (2300° F.); that of Stromboli in March, 1901, was 1150° to 1176° C. (2102° to 2149° F.).

Surface of Lava Flows. — The surfaces of lava flows vary greatly, some being so rough as to make walking dangerous and difficult, while others are comparatively smooth. A fluid lava will consolidate with smooth

FIG. 292. — Pahoehoe type of lava surface in the crater of Kilauea, Hawaii. (U. S. Geol. Surv.)

and ropy surfaces, while a viscous one will become very scoriaceous. This latter condition is partially due to the gas in the lava, which instead of escaping freely to the air forms bubbles in the surface of the lava, just as air blown into soapy water forms a frothy surface; the crust may also be broken to some extent by the continued movement of the more liquid mass below, causing an extremely rough surface when the mass hardens. The Hawaiian word *pahoehoe* is used to designate the smooth type of lava, with the gently rounded, ropy surface which is characteristic of fluid lavas (Fig. 292); while another Hawaiian term *aa* is used for the rough, cindery surface (Fig. 293).

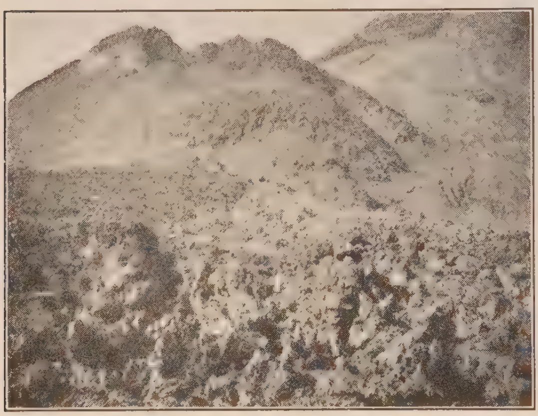


FIG. 293. — The rough *aa* surface of a lava flow on the volcano Colima. Mexico.

Velocity of Lava Flows. — The rate of flow of lava depends upon its fluidity and upon the slope over which it moves. In Iceland lava streams have flowed over surfaces which appear flat to the naked eye, while elsewhere they have consolidated on slopes which were almost vertical. A lava stream on Mauna Loa flowed fifteen miles in two hours, and the main stream from Vesuvius in 1906 descended the first steep slopes with a velocity of about two miles an hour. Such rates as the above are, however, rather unusual. The rate of flow is gradually reduced as the stream cools and as the slope diminishes. Lava often continues moving for a long time after the eruption ceases. A lava stream which began to move on Vesuvius in 1895 was found to be still in motion four years afterward.

Nature of Lavas. — The slag formed in an iron furnace is really an artificial lava, and from it much concerning the nature and behavior of lavas can be learned. When lava is spoken of as a molten rock it should be understood that, since rocks are composed of minerals varying in fusibility and solubility, it is really a liquid rock in which *some mineral matter is dissolved in other mineral matter; i.e.*, it is a mutual solution of mineral matter in mineral matter. Gases as well as mineral matter enter into the solution.

This can best be illustrated by a well-known experiment. If crystals of snow, salt, and sugar are mixed together and compacted at a low temperature, an artificial rock will be formed in which the constituents can be recognized. If the temperature of this solid is now raised to about 32° F. the mass will become a liquid, even though the melting points of salt and sugar are very much higher. In this case, a rise in temperature sufficient to melt but *one* of the constituents is necessary, since this one is then capable of dissolving the others. If the temperature of such a solution is again lowered, the salt and sugar will not crystallize out until they are forced to take the solid form by the crystallization (freezing) of the water. It is evident that both in the process of solution and in that of crystallization the important factor is solubility, and that a temperature merely sufficient to melt *one* of the constituents is necessary.

That lava should be considered as a solution of various minerals is evident when cooled lavas are examined. If lavas were simply molten rocks in which the minerals had melted according to their fusibility, we should find that upon cooling the least fusible mineral would crystallize out first, then the others in the order of their fusibility. Such, however, is not always the case; often the least fusible mineral is the last to take the solid form. This is due to the fact that the *liquid mass is a solution* in which the various minerals assume the liquid state, and upon cooling, the solid state, depending upon their solubility more than upon their fusibility, the least soluble rather than the most infusible crystallizing first.

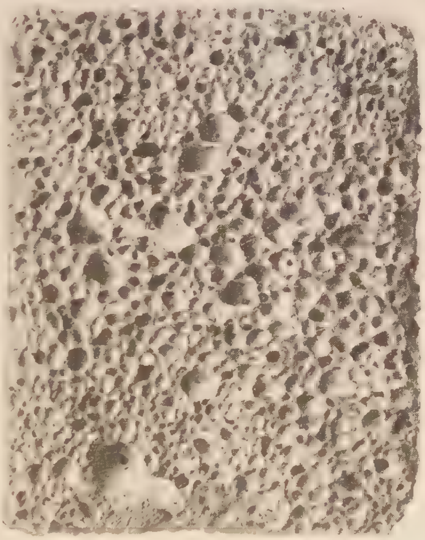


Fig. 294. — Scoriaceous lava. (U. S. National Museum.)

When molten rock cools very slowly, as is usually the case when it is intruded beneath the surface, the molecules of which it is composed tend to collect into crystals. When the process is long continued the point of saturation of the other minerals is reached, crystals are formed, and a rock composed entirely of crystals results. Granite and coarse-grained traps (p. 330) are such rocks. If the cooling is more rapid, rocks composed of fine crystals such as rhyolites and basalts (p. 331) may be formed. When, however, molten rock cools so rapidly that no crystals or only a few can form, volcanic glass, or obsidian, is produced. Often a lava flow passes from a glassy to a crystalline state from the surface downward. When such cooling lava is under little pressure, the gases in the surface portions are able to expand, and often produce a surface which is called *scoriaceous* (Fig. 294) if cindery, or *pumiceous* if the pores are very numerous and small.

Types of Volcanoes

Because of their destructiveness volcanoes probably inspire greater interest than any other natural phenomenon, and it will consequently be well to discuss briefly the various types of volcanoes. It should, however, be remembered that the aggregate work of volcanoes is inconsiderable as compared with that of streams, the ocean, and other less conspicuous forces.

The chemical composition of lavas, as will be seen, has a considerable influence upon the character of eruptions, but the principal factor is the *physical state* of the lava; *i.e.*, whether it is fluid or viscous and stiff. If the molten rock is so liquid that the gases can escape rapidly, they do not accumulate into great bubbles which throw the lava high into the air when they break. If on the other hand the lava is stiff, the gases gather into great bubbles which upon bursting throw out the lava as dust, cinders, and bombs.

I. The Explosive or Vesuvian Type

(1) **Vesuvius.** — Vesuvius has been more carefully studied than any other volcano in the world and is yearly ascended by so many travelers that its value as an illustration is unsurpassed.

Previous to 79 A.D. Vesuvius seemed to be extinct, but before the close of that year a great eruption occurred which destroyed the cities of Herculaneum and Pompeii, and laid waste a great extent of country. During this eruption no lava was poured out, but a large part of the crater was blown off and the outline of the mountain greatly changed. Ash and dust were thrown to great heights and were carried long distances by the wind. Pompeii, at the foot of the mountain, was buried beneath 25 or 30 feet of ash, and Herculaneum beneath 60 feet of mud and ash, the latter being covered by a layer of lava during a later eruption. So completely were these cities hidden that their sites were unknown for more than 1600 years. After this first historical eruption (79 A.D.), which is well described by the younger Pliny in a letter to Tacitus,[1] the volcano was occasionally eruptive until 1139. Then, for a period of almost 500 years, with the exception of one feeble eruption, the volcano seemed again to have become extinct, and the crater was choked with rubbish and covered with trees. In 1631 another violent eruption occurred (Fig. 295); fissures opened in the side of the mountain, through some of which steam and ash were thrown, and four streams of lava poured from the crater, three of which reached the sea. During this eruption the cone was reduced about 525 feet in height. During the eruption in 1906, the main lava stream flowed at a rate of a little less than two miles an hour where the slope was steep, but more slowly when passing over a lower grade. When wooden objects, such as trees, were encountered by this lava stream, they were charred but not burned; some were broken off by the weight of the lava and carried on the surface of the stream. When a large object was reached the lava piled up behind it until it was moved aside, overflowed, or the stream moved around it.

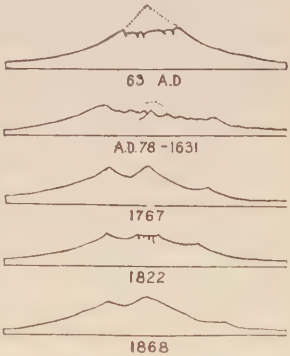


FIG. 295. — Section through Vesuvius, showing the changes in the shape of the volcano between 63 A.D. and 1868. (Philips.)

A summary of the sequence of events in a recent eruption is as follows: In 1904 Vesuvius was almost quiet, but soon explosions occurred of sufficient force to throw fragments short distances above the crater's rim. In 1905 a narrow stream of lava flowed from a fissure in the cone throughout the year. On April 4 of the following year a great cauliflower-shaped cloud of dust and gas rose from the crater, and lava streamed in small quantities from successively lower openings in the side of the cone. On April 7 an explosion occurred which sent a column of dust-laden gas four miles vertically into the air, and new and larger fissures opened through which lava flowed. The dust so weighted the roofs of the houses as to cause them to collapse with loss of life. One lava stream destroyed the town of Boscotrecase.

---

[1] Translation in Shaler's *Aspects of the Earth*, pp. 50–56, or in Lyell's *Principles of Geology*, p. 603.

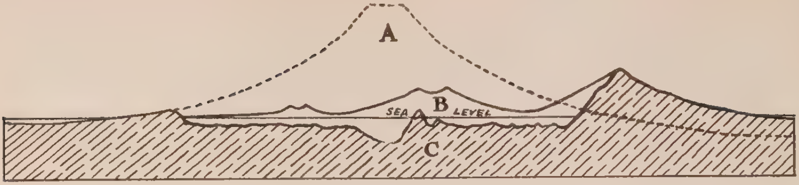


FIG. 296. — This figure shows the changes that have taken place in volcano Krakatao. The outline *A* is what is believed to have been the original profile of the mountain, *B* the profile immediately before the eruption of 1883, and *C* the present outline.

(2) **Krakatao.** — The most stupendous volcanic explosion of modern times occurred in the East Indies when the island of Krakatao, lying between Java and Sumatra, suddenly became eruptive in 1883.

This island was indeed not known to be a volcano, until in August of the above-mentioned year it became violently explosive (Fig. 296) and in two days blew away about one half of its surface, so that now the sea is 1000 feet deep where the central part of the mountain formerly stood. The amount of ash ejected was so great that the

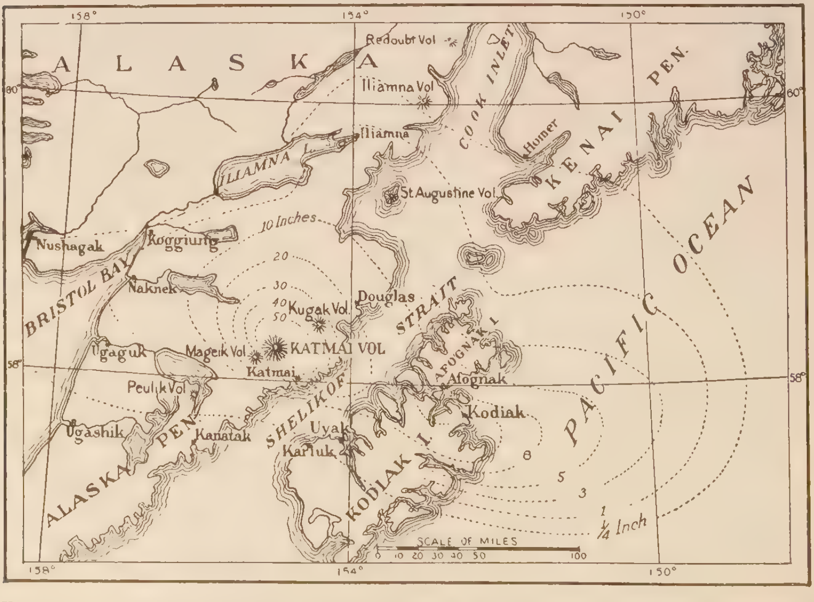


FIG. 297. — Map of a portion of Alaska showing the thickness in inches of the deposit of ash from an eruption of the volcano Katmai in 1912.

neighboring seas and land were in total darkness during the eruption. The ash was thrown to a height of 17 miles, and remained in the air many months, causing brilliant sunrises and sunsets throughout the world (p. 54). Ships 1600 miles away were covered with dust three days after the eruption; stretches of water with an average depth of 117 feet were so filled with the débris as to be no longer navigable. The noise of the explosions was heard 2000 miles away, and the shock produced waves 50 to 80 feet high, which swept the adjacent shores, deluging 1295 villages and drowning about 35,000 people. The height and strength of the waves is well shown in the fact that a large vessel was carried one and one half miles inland and left stranded on land 30 feet above sea level, and that blocks of rock weighing 30 to 50 tons were carried inland two or three miles.

FIG. 298. — A roof collapsed by the weight of ash from Katmai, Alaska, one hundred miles distant. The drift in front of the porch is volcanic ash. (*National Geographic Magazine.*)

(3) **Katmai.** — The eruption of Katmai, a volcano in the Alaskan peninsula, in June, 1912, was one of considerable violence, but one which did little damage because of its situation in an almost uninhabited region. As will be seen from the map (Fig. 297), the fall of ash was 50 inches deep 30 miles from the volcano, and 6 inches deep 160 miles to the east of the mountain. So great was the amount of dust in the air that

100 miles away total darkness prevailed for 60 hours (Fig. 298). The sound of the explosions was carried along the coast for 750 miles.

(4) **Mt. Pelée.** — The eruption of Mt. Pelée (1902) on the island of Martinique in the West Indies was remarkable because of two unusual features. (1) A great blast of highly heated air mingled with incandescent dust swept down one side of the mountain and overwhelmed the town of St. Pierre, killing all but two of its 30,000 inhabitants, one of these being a prisoner in an underground cell to which the air had access only through a small opening. The cause of this mortality was due almost entirely to the fine, hot dust which penetrated into all of the houses and, when breathed, resulted in almost instant death. The reason for the descent of the blast on one side only of the mountain is readily seen when the form of the crater is studied (Fig. 299). With the exception of one place (opposite St. Pierre), where the Rivière Blanche had cut a deep gorge, the rim of the crater was several hundred feet high. When the explosion occurred its force, instead of being expended entirely upward, was partly directed through the gash in the side of the crater, and a great cloud of intensely hot gas, dust, and bombs moved down upon St. Pierre. (2) The second unusual feature was noticed after the principal eruption was over. It consisted in a spine of solid rock rising from the crater (Fig. 300), which began to grow in October, 1902, and reached an elevation of 1000 feet at the end of seven months. Much discussion has arisen as to the origin of this spine, but it is generally believed that it was formed by very stiff lava which solidified into a steep-sided column as rapidly as it was forced to the surface. Other

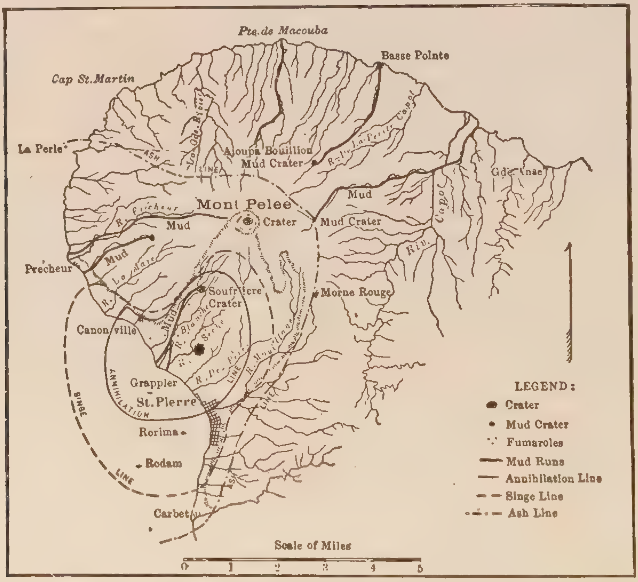


FIG. 299. — Map of Mt. Pelée and environs, showing the portion of the island of Martinique devastated by the volcanic eruption of 1902. The breach in the crater wall is also indicated. (Hill, *National Geographic Magazine.*)

volcanoes are known in which the lava forced out of craters near the close of eruptions assumed the form of steep-sided cones.

(5) **Bandai-san.** — An eruption in which, so far as known, no lava was discharged took place in 1888 in Japan. For 1000 years Bandai-san, a volcanic cone 2000 feet high, had been dormant, when suddenly a terrific explosion blew away the greater part of the mountain (Fig. 301). Since this one explosion, the volcano has shown no signs of activity. The catastrophe was due to the heating of water which had percolated from the surface, and was in fact a steam explosion. A priest living on the mountain reported that the gases surrounding him were respirable.

FIG. 300. — The spine of Mt. Pelée Martinique, French West Indies, 1902. (After E. O. Hovey.)

In all of the eruptions of the explosive type, dust, cinders, and usually bombs are thrown out; earthquakes are prevalent previous to and accompanying the eruptions; sometimes lava is poured out from the crater or from fissures in the mountain side. The greatest eruptions often occur after long periods of inactivity.

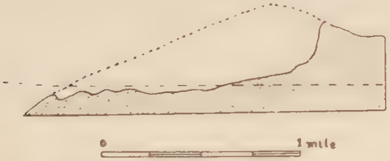


FIG. 301. — Volcano Bandai-san. The portion enclosed by the dotted line was blown off during an eruption lasting less than two hours. The height of the cliff is about 1500 feet. (After Hobbs.)

II. The Quiet or Hawaiian Type

The Hawaiian type of volcano is in marked contrast to the explosive or Vesuvian type, since in the former eruptions are not accompanied by severe explosions, but consist largely in the gentle welling-out of lava from the crater or from mouths in the sides of the mountain. In general, the features most characteristic of volcanoes of this type are: (1) their gentle slopes which do not average more than 7 degrees, (2) the large size of their craters or *calderas*,[1] (3) the quietness of the eruptions, (4) the fusibility of the (basic) lava which they discharge, and (5) the absence of severe earthquakes during and preceding eruptions.

---

[1] See footnote on p. 309 for restricted use of term *caldera*.

The summit of Mauna Loa on the island of Hawaii is 13,675 feet high, while the volcano Kilauea on its flanks 20 miles distant is only about 4000 feet above the sea. Though forming one mountain the two volcanoes are entirely independent, having been joined by the gradual growth of the two cones. The surface near the summit of Mauna Loa is nearly flat for several square miles, and the crater cannot be seen until one is close upon it, the mean slope within a circle of five miles around the crater being about three degrees. If one conceives of the ocean as removed, this volcano (Mauna Loa) would tower above the floor of the sea as a broad-topped mountain, to a height of more than 30,000 feet, with a base many miles in diameter. Every island of the Hawaiian group is of the same nature and is usually built up of lava from several cones. With the exception of Iceland, the island of Hawaii is the largest pile of lava in the world.

Crater of Kilauea. — The caldera of Kilauea will be taken as a type of volcanoes of this class. On the top of the mountain is a great pit, three miles long and two miles wide, surrounded by vertical, terraced walls (Fig. 302). The floor of the caldera is composed of a plain of black lava in which lies a lake of liquid lava of a bright orange color. The surface of the lake, except near the center, is covered by a scum of frothy lava. During eruptions, great volumes of this fiery liquid are thrown many feet into the air. From time to time the surface of the molten lake cools sufficiently to permit it to harden. The lava crust thus formed then cracks, and through the cracks jets and fountains of lava are ejected. The level of the lava floor does not remain stationary, but gradually rises previous to an eruption, sometimes as much as 100 feet a year,

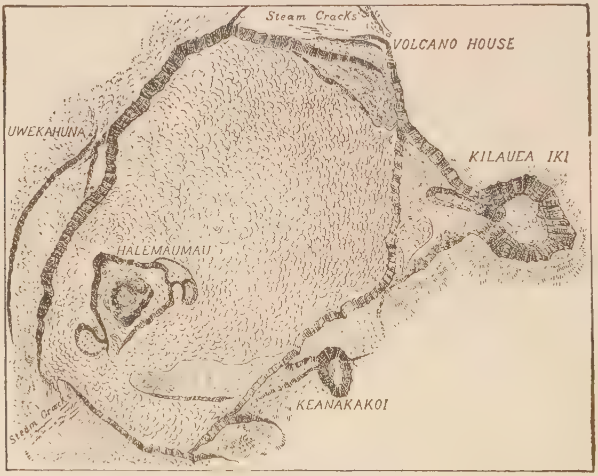


FIG. 302. — Map of the Kilauea caldera, Hawaii, in 1886.

until the lava may reach to within 300 feet of the rim of the crater, but never (in modern times) overflowing it. After the eruption the floor may be 1000 feet below the edge of the crater.

Eruptions. — When the lava rises in the crater, it is evident that the pressure on its walls is greatly increased, since a column of liquid lava 50 feet high exerts a pressure of about 625 pounds to the square inch. The result of this increased pressure is either actually to fracture the mountain and thus to afford an avenue of escape for the lava, or to aid it to break and fuse its way through the porous lava of which the side of the mountain is built. During the eruption of Kilauea in 1840 lava first made its appearance five miles from the main crater; later it sank in this new crater and reappeared at other smaller openings farther down the mountain side; finally, it was poured out on the surface still lower down and flowed in a molten stream to the sea. During the 1919–1920 eruption of Kilauea a great fountain of lava spouted up through a fissure in the side of the mountain "like a wall of red flame" 1000 feet long and 150 feet high.

Lava Streams. — The flow of lava from Kilauea on one occasion "swept away forests in its course, at times parting and inclosing islets of earth and shrubbery, and at other times undermining and bearing along masses of rock and vegetation on its surface. It plunged into the sea with loud detonations. The burning lava, on meeting the waters, was shivered like melted glass into millions of particles, which were thrown up in clouds that darkened the sky and fell like a storm of hail over the surrounding country. The light was visible for over a hundred miles at sea, and at the distance of forty miles fine print could be read at midnight." (J. D. Dana.) Such explosive action, however, does not always take place when lava reaches water, probably because of the cooler and more stony character of the lava. This was true of a lava stream from Vesuvius in 1794, which entered the sea so quietly that it was possible to watch its progress from a boat close to its front.

The tunnels and caves on the Hawaiian volcanoes, caused by the draining out of the lava from below the hardened crust, are hung with lava stalactites 20 to 30 inches long, and stalagmites formed by lava dripping from above project from the floor. Such tunnels are sometimes buried beneath later flows and may later be utilized as outlets for lava, such as occurred during the Kilauea eruption just described, when the lava burst out near the foot of the mountain.

An interesting form of lava found on Kilauea, called Pele's hair, is composed of hair-like threads of lava glass, and in masses resembles tow. It is formed when the wind catches particles of molten lava, either from the lava froth or from the jets thrown up from the crater, and draws them out into glassy threads.

Origin of Calderas. — The craters of the Hawaiian volcanoes have been enlarged by the sinking in of their sides and, as has been said, are called *calderas*. Calderas[1] are also formed as a result of violent explosions which blow off the top of a cone, as was true of Vesuvius during the first historic eruption (p. 302). Calderas are craters of unusual size, varying from one to five or more miles in diameter. One of the most remarkable calderas in the world is that of Crater Lake, Oregon (Fig. 303), which is five to six miles in diameter and 2000 feet deep, the walls standing 900 to 2200 feet above the water. A small cone, called Wizard Island, rises a few hundred feet above the lake. The

---

[1] Daly restricts the term *caldera* to great craters formed by explosions, such as that of Krakatao. The word *sink* is suggested for the Hawaiian and Crater Lake (Oregon) craters, formed by the sinking in of the top of the mountain.

FIG. 303. — A cross section through Crater Lake, Oregon, showing the ancient caldera and the more recent cone, Wizard Island. (U. S. Geol. Surv.)

presence of glacial striæ on the crater rim proves that the summit of the mountain was at one time much higher than now, and that a glacier moved down it over what is now the rim. It is believed that the crater was formed by the sinking in of the top of the mountain, the absence of volcanic ejectamenta about the mountain being proof that the mountain was lowered in this way rather than by an explosion. The craters of the moon are two to twenty times larger in diameter than those of the earth and may have been formed in the same manner as those of the Hawaiian type.

Steep Lava Cones: Volcanoes of the Chimborazo Type. — It should not be concluded from a study of the Hawaiian volcanoes that all lava cones have a gentle slope. When the lava is viscous, steep-sided cones are formed. The great Ecuador volcano, Chimborazo (20,498 feet), is composed of lava and is, moreover, craterless. As the lava welled up from the vent, it left upon cooling no depression in the summit of the mountain.

III. Fissure Eruptions

When lava is very fluid and in great quantity, it may flow long distances and form comparatively level plains many square miles in extent. The most remarkable lava plateau of this kind in North America (Fig. 304) covers an area of 200,000 to 250,000 square miles in Washington, Oregon, Idaho, and California (p. 583). It is a vast plain of black basic lava over which one may ride for many hours on a level surface. The lava which overspread this region poured out from fissures instead of from volcanoes, with little or no explosive action, and since it was very fluid, flowed for long distances, filling the valleys and covering the smaller hills. Some portions of the region were buried hundreds of feet deep, the greatest depth being estimated at 3700 feet. This great plain was not built up by a single great outpouring of lava, but by a number of flows, some of which followed each other in rapid succession. On the other hand, the surfaces of some of the flows were exposed to the action of the weather many years before the next outpouring occurred, as is shown by the thick layers of soil between the lava flows. Previous to the extrusion of the lava the region was a deeply dissected one, but the lava filled the valleys, buried the lower hills, and surrounded some of the mountains, leaving them as islands in a molten sea. The border of the lava plateau is very irregular, since ridges and spurs extend into it from the higher land, and it in turn protrudes long fingers between the mountain masses. The edge of the sheet can best be compared to the shore line of a submerged coast (p. 226).

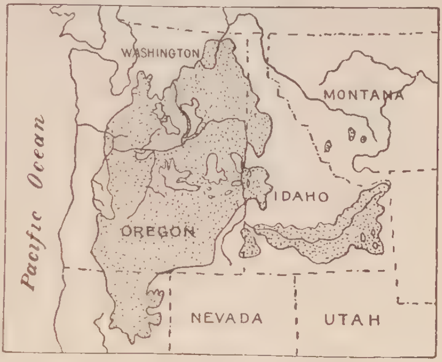


FIG. 304. — Lava fields in Washington, Oregon, Idaho, and California.

Recent Icelandic Lava Sheets. — Much of the nature of such lava plains as those described can be learned from a study of recent eruptions in Iceland, a region which exhibits marks of igneous activity in greater variety and magnitude than any other spot in the world. In 1783 lava welled out for several months from the great Laki fissure. This fissure is 20 miles long, and on it were formed more than one hundred low craters, from which sheets of lava were spread out on either side (Fig. 291, p. 298). From the place of eruption the lava stream flowed 47 miles on one side and 28 miles on the other, covering an area of 220 square miles to an average depth of 100 feet. The longest flow on record in Iceland is 90 miles, the slope of which is so gentle as to be almost imperceptible, the angle being only a little more than one half of a degree. In some cases lava has welled up from fissures in Iceland without the formation of cones; the longest flow of this class is 19 miles. In other parts the lava has built up great domes similar to those in Hawaii; one of these is 4600 feet high, with an elliptical crater about three quarters of a mile across at its widest point.

In 1913 a fissure three miles long was formed in Iceland from craters on which lava poured forth and covered the plains. In some cases, the lava shot up in a jet like a geyser; in others, it flowed out like a fiery waterfall.

CHARACTERISTICS OF VOLCANIC CONES

Profiles of Volcanoes. — The slope of a volcanic cone, as has been seen, depends upon the character of the material of which it is made. If it is composed entirely of cinders and ash, the slope will be at the angle of repose, which may be as great as 30° or 40° for coarse ash or cinders (Fig. 305 *A*). The slope is more gentle, however, at the base of the cone, since the dust is carried farther from the summit than the coarser material and is washed farther still by rain and rills. If the cone is of lava, its slope will depend upon the fluidity of the lava. Volcanic cones built of basic lava usually have broad, flattened domes (Fig. 305 *B*), since such lava cools at a low temperature and consequently may remain liquid for a considerable time and flow long distances before solidifying. The Hawaiian and Icelandic volcanoes are examples. If stiff, viscous lava is discharged, the slope may be very steep (Fig. 307). Cones made of a combination of lava and ash are more common than any others and are usually steep-sided. The volcano Fuji, so often pictured by the Japanese artists, is of this type, as are many of the highest volcanoes of the world.

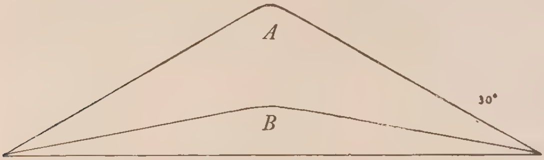


FIG. 305. — Angle of slope of volcanoes. A cone composed of ash will be steep, as much as 30°, while that of lava may not be more than 9°, as in the Hawaiian Islands.

A volcanic cone is seldom symmetrical, since if it has been long in existence it has suffered many changes (Fig. 306). The irregular outline of Vesuvius, as has been seen, is the result of the blowing off of the greater part of an earlier crater, so that the present cone is partially surrounded by Mt. Somma, a remnant of the ancient crater. The slopes of Etna are roughened by scores of parasitic cones. The volcano Colima, in Mexico (Fig. 308), would be beautifully symmetrical were it not for a cone formed on the flanks of the mountain in 1869. This secondary cone is craterless, showing that near the close of the eruption the lava was so

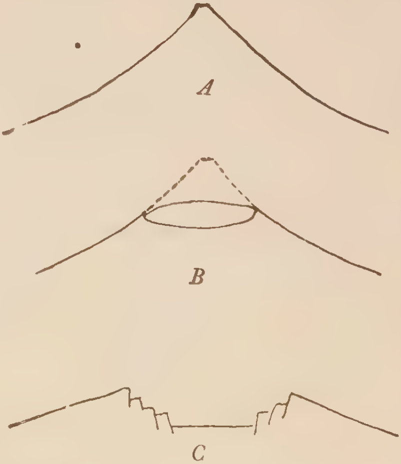


FIG. 306. — Outlines of volcanic cones: *A*, a cone formed of ash; *B*, a cone from which the top was blown by a great explosion; *C*, a caldera formed by faulting.

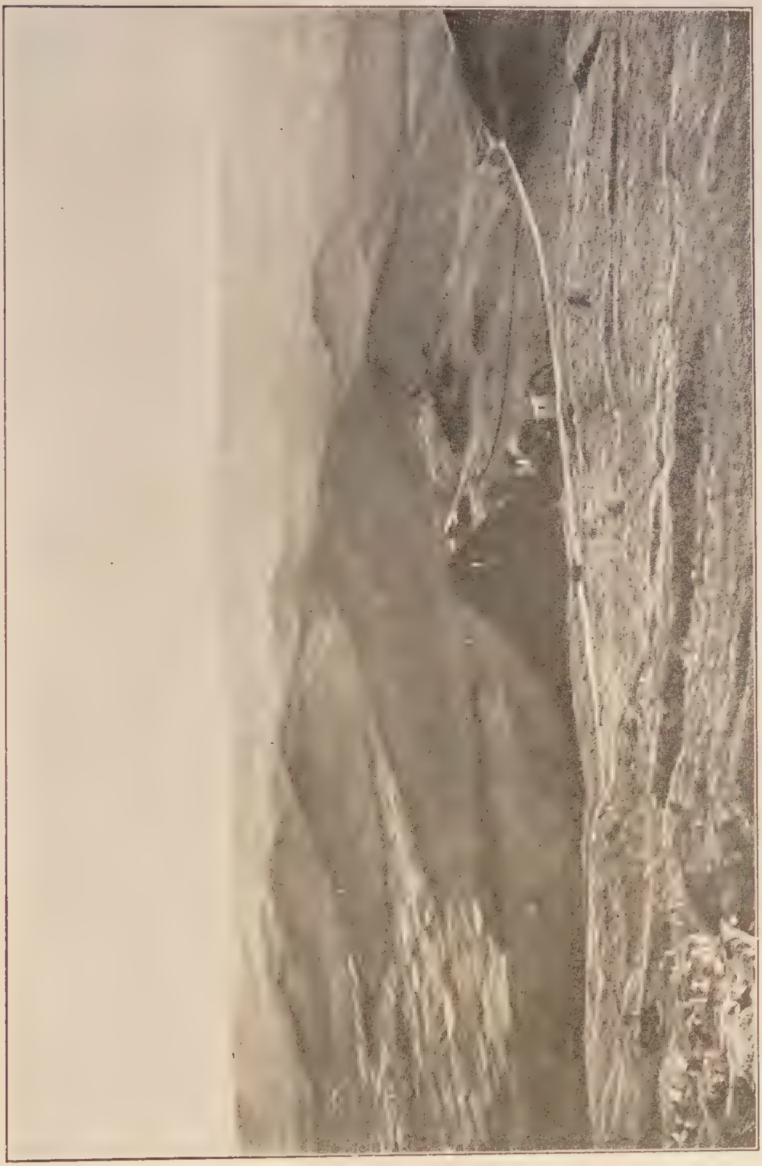


Fig. 307. The line of volcanic cones (Puys) from Puy de Dôme, France.

stiff that it solidified as soon as it reached the surface. The profile of a cone depends also, to a greater or less degree, upon the force and direction of the wind during eruptions, upon the position of the crater, and upon the amount of erosion which it has suffered.

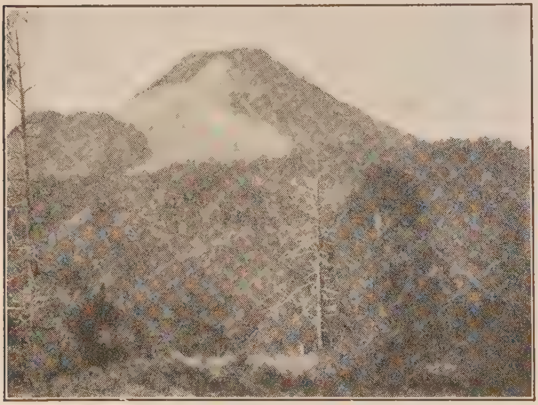


FIG. 308. — Volcano Colima and a secondary cone on the left.

Shape of Craters. — The shape of the crater of a volcano depends both upon (1) the violence of the explosions, the diameter of the crater of an explosive volcano being, in general, proportional to the violence of the eruption; and upon (2) the character of the materials. A crater has steep, rugged inner walls if lava and coarse cinders are ejected (Fig. 309 *A*), but a much less steep slope if dust and fine ash are thrown out and fall back into it (Fig. 309 *B*).

Erosion of Volcanic Cones. — Up to this point we have discussed the phenomena of an eruption, the shape of cones and craters, and other features connected with recent volcanoes, but aside from these observations, we have learned little of the internal structure of volcanic cones. The structure is, however, revealed to us by an examination of ancient volcanoes which have been deeply eroded by atmospheric agencies or by the sea (Fig. 310). Great explosions also, as we have seen in the case of Krakatao, expose the internal structure to some extent, and it is also brought to light when the top of the volcano sinks in, as in the case of Crater Lake, Oregon (p. 309).

FIG. 309. — *A*, a cone formed of coarse fragments; *B*, a cone formed of ash. (After Haug.)

As long as a volcano remains active, the ravages of rain and torrents are repaired by the material ejected, but when it becomes extinct the work of denudation continues uninterruptedly. The rate of erosion varies greatly, depending upon the nature and structure of the materials and upon the climate. Cones composed of coarse cinders are likely to endure a longer time than those of dust. They are more porous and therefore absorb the rain falling on them to so large a degree that little water is left for erosion. Even before a volcano becomes extinct, deep V-shaped valleys are cut into its sides. We find also that the dust and ash are in layers, and that sometimes black beds (Fig. 311) composed of disintegrated ash and humus, varying from a few inches to several feet in thickness, are interbedded with the ash. These black beds are ancient soils and prove that in the past the volcano experienced many years of inactivity, which were followed by eruptions.

Fig. 310. — Rocks, St. Paul Island; a volcanic cone dissected by the waves until the crater has been reached, forming a harbor.

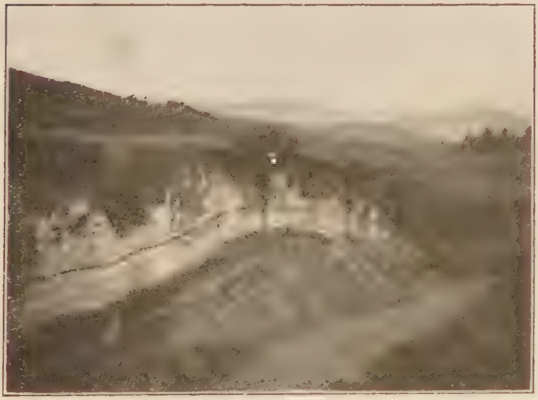


Fig. 311. — A ravine (baranca) in the side of the volcano Toluca, Mexico. The light-colored deposit is volcanic ash; the dark bands are ancient soils which prove long periods of quiet after periods of activity.

After prolonged erosion it often happens that long, wall-like bodies of hardened lava, called dikes (p. 324), are exposed. These dikes were formed during eruptions, when the force of the explosions or the pressure of the column of lava in the vent was so great as actually to rend the cone. Into these cracks the lava was forced and cooled. It will readily be seen that a cone buttressed by dikes will be greatly strengthened, and that such a cone will be better able to withstand erosion than one composed entirely of fragmental materials.

Necks and Plugs. — After the upper portion of a cone has disappeared, the *neck* (Fig. 312), as the compact lava or débris filling the vent is called, is exposed. The neck is composed either of lava or of the rocks or other fragmental materials which fell back into the crater and were consolidated to form a volcanic breccia. They vary in diameter from a few yards to two miles. Volcanic necks or *plugs*, when exposed by erosion, are often conspicuous features of the landscape. Many examples are to be found in North America. From Montreal one can see several hills of this origin. In New Mexico, Arizona, California, and other western states of the United States volcanic necks are to be seen. They are not uncommon in portions of Europe, where they are frequently the sites of castles or churches (Figs. 313, 314). When erosion has succeeded in entirely tearing down a volcanic cone, it is often found that the neck pierced the surrounding rock without the aid of a fissure or fault, and that it is independent of the folds of the rocks. The great diamond mines of South Africa are

Fig. 312. — Diagram illustrating the destruction of volcanoes. (After A. Geikie.)

Fig. 313. — Volcanic neck upon which a chapel has been built. Le Puy, France.

located in the necks of volcanoes, the brecciated rock of which is called "blue ground" and contains the gems. These latter necks have a diameter of 300 to 1000 feet.

FIG. 314. — Volcanic neck in the Mt. Taylor region, New Mexico. (Photo. D. W. Johnson.)

Stages of Erosion of Volcanoes. — In regions of extinct volcanoes every stage in the process of demolition may be studied (Fig. 315 *A*, *B*), from the perfect cone, whose slopes have as yet barely been touched by erosion, to that in which the only evidence that a volcano formerly existed is to be found in a spot of igneous rock, a few feet or a few hundred feet in diameter, surrounded by sedimentary or other rock. The various stages in the erosion of volcanic cones are well shown in the western United States, where every gradation may

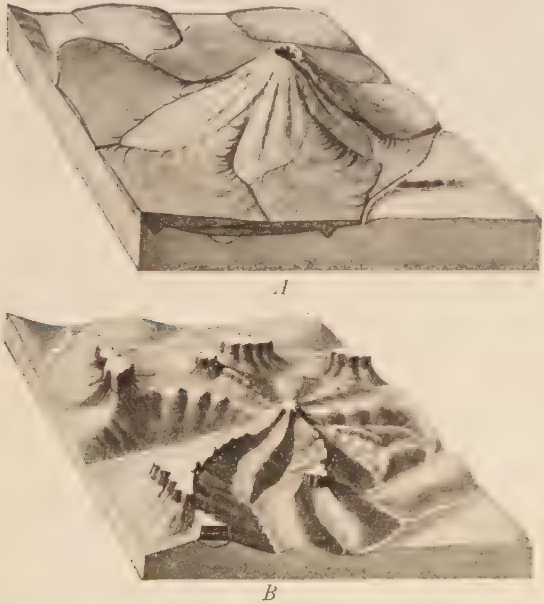


FIG. 315. — Diagram *A* shows an active or recently extinct volcano with widespread lava flows at its base. Diagram *B* is the same region after prolonged erosion. The ash of which the cone was composed has been eroded away, leaving the volcanic neck protruding. The lava flows have been cut by erosion into flat-topped hills or mesas. In the section on the front of *A* the former successive positions of the streams are shown, their courses having been diverted as they were filled with lava from the volcano. (Modified after Davis.)

be seen from young cones, such as Lassen Peak, California, which was active in 1914-1915, to those which have been worn down to their roots. Mt. Shasta, California, 14,350 feet high (Fig. 316), is a good example of a volcano which has suffered much erosion, but Mt. Hood, Oregon, is still more worn, the sides being deeply trenched by ravines and only a part of the wall of the crater being left.

FIG. 316. — Mt. Shasta, California, a partly denuded volcanic cone.

DISTRIBUTION AND NUMBER OF VOLCANOES

Number of Volcanoes. — It is impossible to determine accurately the number of active volcanoes, since some that appear to be extinct may be merely dormant, and others that have recently been active and from which steam is still rising, may have been in eruption for the last time. It is, moreover, sometimes difficult to distinguish between independent and subsidiary vents. It is safe to say that there are approximately 325 active volcanoes, of which one third are on the continents.

Distribution. — A glance at a map of the world in which the volcanoes are conspicuously indicated (Fig. 317) shows some striking features of their distribution. It is seen that they are not scattered haphazard over the world, but are for the most part concentrated along lines or belts near the edges of the continents, and dot limited areas of the oceans. The volcanic belts are not continuous, how-

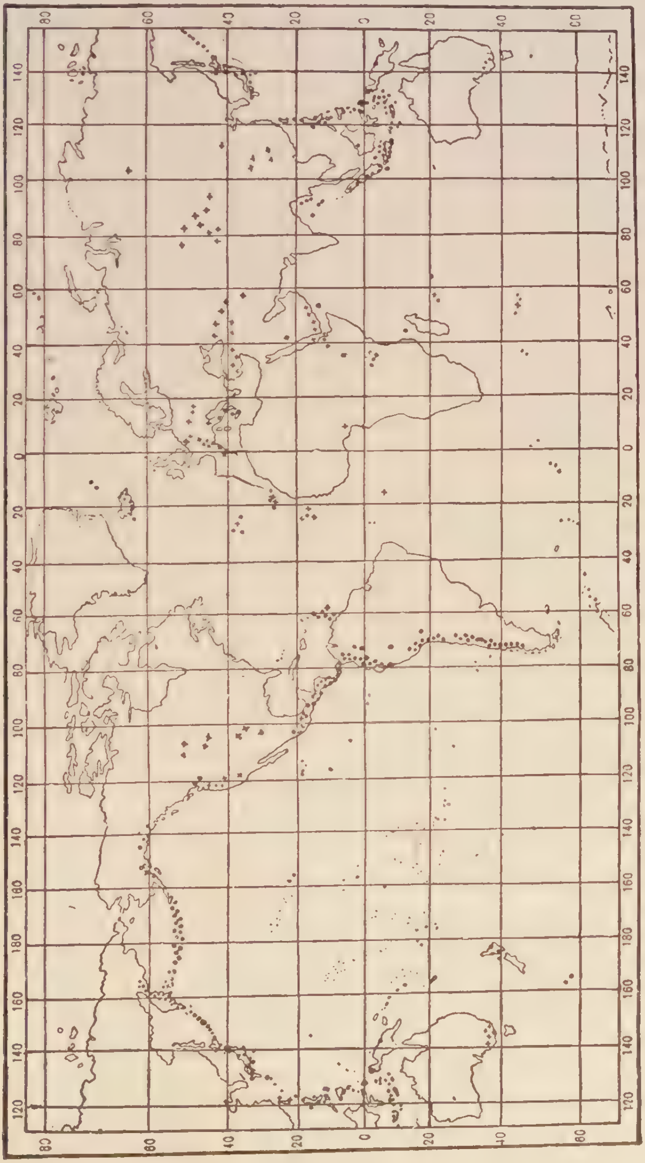


Fig. 317. — Map showing the distribution of active volcanoes, represented by dots, and recently extinct volcanoes, represented by crosses. (After Russell.)

ever, but are interrupted in many places by areas in which no volcanoes occur.

Although volcanoes are usually situated along the borders of continents, this is not always the case; some volcanoes in Ecuador, for example, are 150 miles inland, and in East Africa the volcano Kirunga is 600 miles from the coast.

The most important of the volcanic belts almost encircles the Pacific Ocean, extending from the southern tip of South America northward along the Andes on the western coast of that continent, through Mexico, and along the western coast of North America to Alaska. From Alaska it curves westward and southward through the Japanese and Philippine archipelagoes to New Zealand and to the Antarctic volcanoes. The borders of the Atlantic, in contrast to those of the Pacific, are almost free from volcanoes. Two important belts, however, occur in this ocean; one stretches from Iceland south to St. Helena and includes the Azores and other volcanic islands; the other includes the West Indies and the shores of the Mediterranean Sea.

Cause of Distribution. — A study of regions of volcanic activity brings out the fact that they have recently undergone severe movements, or are actually being deformed at the present time. In other words, volcanoes are situated where mountain-making forces (p. 358) are active, and where, consequently, the earth is much fissured and fractured (p. 360). The fact that belts of active volcanoes are usually found where mountain ranges are near or parallel to great deeps in the neighboring oceans has given rise to the belief that the elevation of the strata of which mountain ranges or islands are composed is compensated by a sinking of the ocean bottom, and that as a result of these movements lava and ash are ejected to form volcanoes. It is to be noted in this connection that volcanic activity tends to die out in the older rocks and to appear in those of later date.

It is evident from the above that the problem of the distribution of volcanoes is an important one, since on its solution must depend in a large measure the much more general one of the cause of volcanism.

Ancient Volcanoes. — The volcanoes of the past had as a rule a different distribution from those of the present. For example, Great Britain and central France were the scenes of intense volcanic activity; the Connecticut valley, northern New Jersey, and many of the western states (Wyoming, Colorado, New Mexico, Idaho, and others) have experienced great lava flows, or many and great volcanic eruptions. At a much earlier period in the earth's history (Pre-Cambrian) volcanism appears to have been widespread in eastern and central Canada, and large areas in Wisconsin and Minnesota are underlain chiefly with volcanic rock. Throughout geologic history periods of unusual volcanism have been followed by others of comparative quiet. The last important period of volcanism preceded the advent of the Great Ice Age (p. 643), and it is possible that we are now living in the declining phases of the activity of that time.

IMPORTANCE OF VOLCANISM TO MAN

(1) *Beneficial Effects.* Volcanic regions are interesting not only because of the striking character of their phenomena and scenery, but also because of their economic value. Abundant springs are usually found in the neighborhood of volcanoes. The ashes from recent eruptions often form a fertile and easily worked soil. When the surfaces of flows composed of dark-colored lavas (basic, p. 329) are decomposed, they furnish a soil which contains all of the elements needful for plant life, many of which are lacking in granite and other soils; in Central America, certain regions are benefited far more than they are injured by the showers of volcanic ash, because of the increased fertility resulting from the minerals which these contain. Vesuvius is surrounded by a ring of villages in spite of the danger of eruptions, and the flanks of Etna support an extremely dense population.

Of benefit to man also, are the many lakes that rest in the craters of inactive volcanoes. The lakes of the Alban Hills near Rome, as well as Lake Bracciano and other lakes of Italy, are crater lakes. Crater Lake in Oregon (p. 309) is also a famous example. Lakes have also been formed by the damming of river valleys by lava streams. At the foot of Mt. Shasta, California, are rich tracts of alluvium, the sites of lakes formed in this way and later filled by deposits which now constitute rich agricultural land.

Many important ore deposits (p. 371) have resulted from the intrusion of molten rock.

(2) *Harmful Effects.* Although volcanoes are sometimes indirectly beneficial to man, this does not compensate for the destruction of life and property which result from an eruption. In addition to the destruction wrought by the fall of ash and the outpouring of lava, great disaster has been caused in other ways. Many times in the past, great floods have been brought about by the discharge of the water from lakes which rested in craters, and by the melting of

the snow and ice on and near the summits of the volcanoes. During an eruption of Cotopaxi in 1877 enormous torrents of water and mud produced by the melting of the snow and ice on the cone, together with great blocks of ice from the glaciers, rushed down the mountain, burying fields and villages beneath mud, lava, and ice for a distance of 10 miles. In contrast to the above is the existence of a great sheet of ice on Mt. Etna, which for nearly one hundred years has been protected from evaporation and thaw by a sheet of lava which overflowed it without the heat being sufficient to melt it.

As torrents of water rush down the side of a volcano, they not only erode it deeply but are also soon converted into streams of mud, when dust and ash are abundant on the cone. Herculaneum (p. 303) was buried in this manner, and in Java in 1881 torrents of mud and water from Galoon-goon flooded the rivers to such an extent that every village and plantation in this populous region was entirely destroyed for a distance of 24 miles.

During a comparatively recent eruption of Vesuvius so much hydrochloric acid was dissolved in the rain water which fell through the clouds of volcanic gases that the vegetation for miles around was injured by it.

A subsidence of the land sometimes follows an eruption, as has been noted in the case of the Temple of Jupiter near Naples (p. 229). The sinking is probably brought about either by the withdrawal of molten rock from beneath the affected areas or by the weighting of the adjacent land by the ejected material, or by a combination of both.

Volcanoes and Climate.[1] — It has been shown that volcanic dust in the high atmosphere decreases the intensity of solar radiation in the lower atmosphere. Therefore the average temperature of the earth is decreased when dust is present. From these observations some investigators have concluded that volcanic dust must have been a factor, possibly an important one, in the production of many climatic changes of the past. It has not, however, been shown that the periods of glaciation coincided with prolonged volcanic outbursts.

SUBORDINATE VOLCANIC PHENOMENA

There are a number of phenomena which are the direct result of heat and are usually connected with present or comparatively recent volcanism.

---

[1] Bull. Mt. Weather Observatory, Vol. 6, Pt. I, 1913; Smithsonian Misc. Coll., Vol. 59, No. 29, 1913.

Mud Volcanoes. — Cones built of mud with small craters in their summits are called *mud volcanoes*. They range in height from a foot or two to more than a hundred feet; some are continuously active and some are intermittent; some are quiet and a few are violently eruptive. In order that mud volcanoes may be formed it is necessary that (1) steam be present and that (2) it rise through a surface layer of clay which will make mud when wet. As the steam rises through the mud, it carries some up with it and so builds a cone. As such cones are composed of soft material, they have a short life, since they are readily destroyed by rains. The heat and steam necessary for the formation of mud volcanoes come from lavas which are present at a comparatively little depth, or may be produced by chemical action, such as occurs when sulphur is oxidized. Mud volcanoes are found in the Colorado desert, in Lower California (Fig. 318), and in other parts of the world. The "paint pots" of the Yellowstone National Park, so-called because of their shape and varied colors, are miniature mud volcanoes. The eruptions, produced by the bursting of bubbles of steam, occur frequently, and can be safely and easily studied.

FIG. 318. — Mud volcanoes, Lower California. (Photo. D. T. MacDougal.)

Solfataras. — Lava streams sometimes retain their heat hundreds of years after they have been poured out in sufficient amount to convert the water which percolates to them into steam. This is also true of the lava in the craters of volcanoes. Although meteoric waters probably furnish the greater amount of water which is returned as steam, yet the quantity of steam exhaled directly from lavas appears to be considerable in some cases. The term *solfatara* is used for a volcanic vent or area in which only gases and steam are discharged, the name being derived from the volcano Solfatara near Naples, which has been giving off only steam and gases since its last eruption (in 1198).

Geysers (p. 67) are found only in regions in which acidic lava is still hot, and hot, carbonated springs (p. 66) occur in similar situations, although their heat does not always have this origin.

Intrusive or Plutonic Rocks

Igneous rocks have either been extruded on the surface in the form of volcanic products and lava flows, or they have failed to reach the surface and have consolidated beneath it. The latter are called *plutonic* (after *Pluto*, the Greek god of the lower world) or *intrusive* rocks. The quantity of molten rock which failed to reach the surface is probably many times greater than that which was poured upon it. The deep-seated intrusive rocks are never vesicular (full of gas blebs), since their contained gases were prevented from expanding by the overlying pressure. They are coarsely crystalline because they cooled so slowly, owing to the fact that they were deeply buried, so that the crystals had time to grow. Such rocks are exposed at the surface only by the erosion of the rock strata which formerly covered them. Doubtless many such masses, now exposed at the surface, were at one time the deep-seated reservoirs from which the lava of volcanoes came. There are some rocks which link the extrusive and the plutonic rocks and may be classed simply as intermediate.

Fig. 319. — A vertical, branching dike. (Photo. F. B. Sayre.)

The mechanics of igneous intrusions is discussed on page 334. It will be shown that intrusions probably work their way toward the surface largely by *stoping* (p. 337). When they have reached within a few thousand feet of the earth's surface, they take advantage of any planes of weakness, such as joints and faults, and continue their journey through fissures.

I. Injected Masses

Dikes. — Dikes are masses of igneous rock which have hardened in more or less vertical cracks or fissures (Fig. 319).

They vary in width from a fraction of an inch to several hundred feet. Their length may be considerable; one in the north of England runs from the coast inland for about 100 miles, and a length of 5 to 20 miles is not uncommon. In Scotland a series of dikes extend parallel to each other for a distance of from 20 to 30 miles, while on the coast of New England and in many other parts of North America they are very common. When the surrounding rocks decay more easily than the dike rocks, the latter project above the surface of the ground like walls (Fig. 320) and are sometimes used in Scotland as inclosures. Near Spanish Peaks, Colorado, a dike stands as a great wall 100 feet high. Occasionally the dike rock weathers more readily than that which it cuts (Fig. 321), in which case the position of the dike may be indicated by a trench-like hollow. If the dike and the surrounding rocks are about equally resistant, no topographic features result.

Fig. 320. — Dikes cutting flat-lying Eocene strata. West Spanish Peak, Colorado. (U. S. Geol. Surv.)

Fig. 321. — Diagram showing the effect of weathering upon two dikes (shown by horizontal lines), one of which is more resistant than the surrounding rock and the other less resistant.

The texture of the rocks of dikes depends upon a number of conditions: (1) if the fissure through which the magma was forced was narrow, the rock of the dike is either glassy or finely crystalline; (2) if, however, the fissure was wide, the dike rock may be coarsely crystalline, with narrow margins of less crystalline or glassy rock.

Dikes are found cutting rocks of all ages, and they extend across the country without reference to topography.

Sills. — Magmas which have been forced between sedimentary strata and have formed sheets which have a small thickness as compared with their extent are called *sills* (Fig. 322). Sills sometimes extend long distances along the same bedding plane, but many cut across from one stratum to another. They vary in thickness from a few feet to several hundred feet and sometimes have an extent of many square miles. When they have been exposed by erosion, they can be distinguished from extruded lavas by the absence of vesicular lava on the upper surface. The Palisades of the Hudson, which extend for 30 miles along the west bank of the river as a bold cliff several hundred feet high, form a part of a great intrusive sheet (sill) which is underlain by sandstone and was formerly overlain by other sedimentary strata (Fig. 323).

FIG. 322. — Diagram illustrating the relation of the Palisades of the Hudson (vertical lines) to the strata in which this sill was intruded.

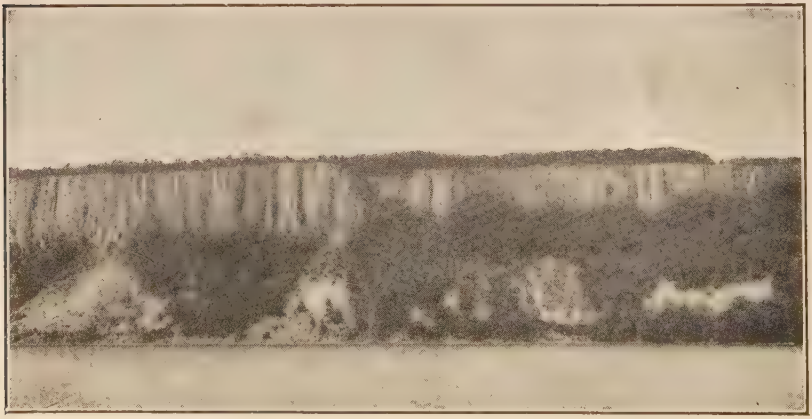


FIG. 323. — The Palisades of the Hudson. The sheer face of the upper portion is due to the vertical jointing of the trap, and to the more rapid erosion of the weaker, underlying rock. (Photo. D. W. Johnson.)

Laccoliths (Greek, *lakkos*, a cistern, and *lithos*, stone). — This term has been given to mushroom-shaped intrusions of magma which have been forced along bedding planes and have domed up the overlying strata. They are formed when molten rock rising through a pipe or fissure is unable to break through the overlying rock and spreads between the strata, lifting them and thus producing dome-like elevations (Figs. 324, 325). The difference between a sill and a laccolith is consequently a difference in the degree of the doming of the overlying strata. Laccoliths may be a mile or more thick and a number of miles in diameter. Mountains of considerable height have been formed in this way. The Henry Mountains of southern Utah, the Elk Mountains of Colorado, and many other elevations in the Rocky Mountains are laccoliths (Fig. 325). Laccoliths are composed of magma which was probably stiff and viscous and could consequently more easily lift the strata than force its way between them. The magmas of sills, on the other hand, were probably quite fluid and therefore could spread long distances.

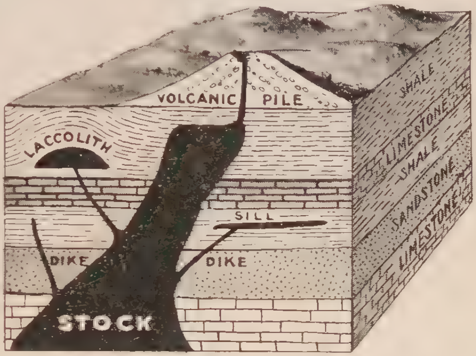


FIG. 324. — Block diagram to show the form and relations of dikes, sills, and laccoliths.

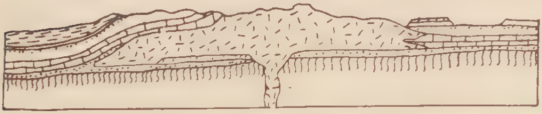


FIG. 325. — Diagram of a laccolith, showing the relation of the igneous intrusion to the overlying and underlying strata.

II. *Subjacent Masses*

Stocks. — The name *stock* is applied to large bodies of igneous rock lying in the midst of other formations. Stocks are usually circular or elliptical in outline and vary from a few hundred yards to many square miles in extent, usually increasing in size downward (Fig. 326 *A*, *B*). Since they are composed of more resistant rock than that in which they were intruded, they often form knob-like elevations and are consequently often called *bosses*. Stocks resemble volcanic necks (p. 316), but are usually larger; the term *neck*, moreover, is employed only when there is evidence that it represents the chimney of a volcano.

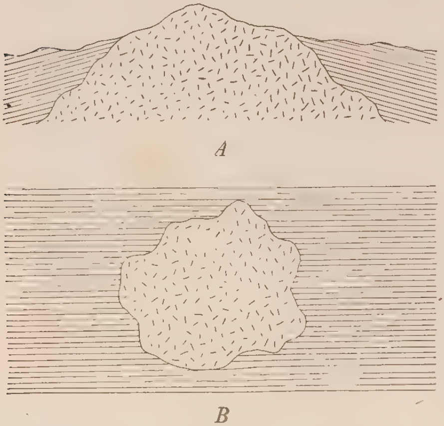


FIG. 326. — Section *A* and map *B* of a stock or boss. The granite intrusion being more resistant than the enclosing rock forms a hill.

Batholiths (Greek, *bathos*, depth, and *lithos*, stone) are great irregular masses of igneous rock which stopped in their rise many feet from the surface of the earth, but have since been exposed by erosion. They are often many hundreds of square miles in area and may be considered as merely very large and irregular stocks.

In the aggregate these bodies cover many thousands of square miles, and although less striking are much more important than volcanoes.

Some Effects of Intrusions. — The rock with which a molten magma comes in contact is more or less changed; the larger and hotter the intrusions the greater being the effect. This phenomenon will be discussed under metamorphism (p. 341). It is believed that some of the explosions which have taken place on or near volcanoes were due to the presence of molten rock at a short distance below the surface. Since igneous rocks are usually harder than those into which they are intruded, they are often left in relief as buttes (p. 106) and bosses, as the land is reduced by erosion.

Since igneous rocks are composed of minerals which differ in composition and often in color and therefore expand and contract differently when heated and cooled, we find in desert and tropical regions that granites and other igneous rocks exfoliate (p. 32) under the influence of diurnal temperature changes (p. 31), producing spheroidal bowlders which are often poised on rounded surfaces. These rocks resemble glacial bowlders, and the smooth surfaces on which they rest, roches moutonnées (Fig. 142, p. 157).

Igneous Rocks

Igneous rocks, as we have seen, have consolidated from a state of fusion. The character of the rocks thus formed depends principally (1) upon the chemical composition of the molten mass and (2) upon the rapidity with which the magma cooled. Other conditions, such as fluidity and pressure, are likewise important.

Subdivisions Depending upon Chemical Composition. — Igneous rocks which contain a large percentage of silica (65 per cent. or more) are termed *acid rocks*, silica being an acid-forming oxide. Acid rocks are usually light-colored when crystalline, and are lighter in weight than *basic rocks* which contain much less silica (55 per cent. or less) and a correspondingly larger amount of the bases, such as potash, soda, lime, and magnesium. Basic rocks are usually dark-colored and fuse at a lower temperature (p. 299) than acid rocks. They are the common extrusive rocks and sometimes cover tens of thousands of square miles of the earth's surface, and when weathered often produce soil rich in plant food.

Subdivisions Depending upon Texture. — The term *texture* as applied to igneous rocks refers to their smaller features. When a rock is described as being *granitoid*, or having a *granular* texture, the reference is to one in which the crystals are distinct and are all of about the same size. A rock with a *felsitic texture* is one composed of a mass of very fine microscopic crystals. A rock is described as *glassy* when it is made up largely or in part of glass in which no definite crystals are to be seen.

The rate of cooling appears to be the really important factor in determining the texture of igneous rocks, although other conditions have considerable effect. The molten magma from which granitoid rocks were crystallized was so deeply buried that the rate of cooling was slow, thus giving an opportunity for the molecules of the same chemical composition to gather to form large crystals and, consequently, *granitoid* or *granular* rocks. *Felsitic rocks*[1] are the result of somewhat more rapid cooling, and are found on the margins of great masses of granitoid rocks which did not reach the surface, or in offshoots from them in the form of dikes. *Glassy rocks* are those which cooled so rapidly that the minerals had little opportunity to form. Rocks with a glassy texture, consequently, occur chiefly in surface flows and on the margins of dikes.

---

[1] Felsite is also often the product of the devitrification of glassy rocks.

Classification of Igneous Rocks

I. Coarse-grained Igneous Rocks

The rocks included in this group are those whose mineral grains are approximately of equal size and are large enough to be distinctly seen.

Granite. — Granites are composed of quartz, feldspar, and usually of smaller amounts of either mica or hornblende. The grains of feldspar are usually easily distinguishable because of their shiny (cleavage) surfaces and their opaque white, gray, or red color. The quartz grains vary in tint from colorlessness to smoky gray, and can usually be recognized by their glassy luster and irregular fracture. Mica may be either muscovite or biotite, and may be told by its brilliant cleavage surface. The thin leaves, unless too small, can be easily separated with the point of a penknife. Hornblende occurs in green to black opaque grains or needles. Other minerals, such as pyrite or garnet and other less common minerals, may also be present.

Numerous names are given to granites, some of them (commercial) depending upon their color and their desirability for building or monumental purposes, such as red, gray, yellow; while others are locality names. The color of the stone depends largely upon that of the feldspar, and upon the relative abundance of dark minerals. A red granite owes its color to its red feldspar; a gray color may be due either to the color of the feldspar alone, or to the combination of black hornblende or mica, and white feldspar.

Syenite is a rock which may be described as a granite without quartz. It very closely resembles a granite, and is usually sold under the latter name.

Diorite is a granular igneous rock composed of hornblende and feldspar of any kind, in which the amount of hornblende usually exceeds that of the feldspar, although the two may be in equal amounts. Its color is dark gray or greenish.

Gabbro is made up of pyroxene (augite), with usually smaller amounts of feldspar of any kind. Gabbro and diorite are often distinguished with difficulty, because of the similarity of hornblende and augite to the naked eye.

Peridotite is a dark green to black rock, composed chiefly of such minerals as hornblende, olivine, and pyroxene (augite).

II. Compact or Fine-grained Igneous Rocks

In this group are included rocks in which the grains are so fine that the individual crystals cannot be distinguished by the naked eye. They are intermediate between the granitoid rocks, composed of clearly distinguishable crystals, and the glasses. No definite line can be drawn between the two groups; in some dikes, for example, a glass shades imperceptibly into a microcrystalline rock, and then into a coarsely crystalline or granitoid rock.

This group is divided into two classes on the basis of color: (1) the light *felsites* and (2) the dark *basalts*.

(1) **Felsites** vary greatly in color, but are *not* dark gray, dark green, or black. To the naked eye the rock has a flinty aspect, but with a lens it is often seen that it consists of mineral grains, too small for determination. When large crystals (phenocrysts) occur embedded in the fine-grained "ground mass," the rock is called a *felsite porphyry*. Porphyries contain feldspar phenocrysts (Greek, *phainesthai*, to appear, and *krystallos*, crystal). If quartz is also present, they are known as *quartz porphyries*, and if hornblende is conspicuous, they are called *hornblende porphyries*. Felsites occur in dikes and sheets.

(2) **Basalts** form a very large and important group of igneous rocks. They are all heavy black, gray, brown, or greenish rocks of fine texture, and have a wide distribution, covering many thousands of square miles of the earth's surface. The name *trap* is also used to include basalts and any dark-colored, heavy igneous rocks whose mineral constituents have not been determined.

When the air cavities of vesicular basalts or of other igneous rocks are filled with minerals, the rocks are called *amygdaloidal*. This is one mode of occurrence of copper in some of the mines of northern Michigan (p. 396).

III. Glassy Rocks

Rocks which are composed partly or wholly of glass are included in this group. They were formed as stated (p. 329), when molten rock solidified rapidly. They are therefore lavas which were either poured out on the surface, or in crevices where they were subjected to rapid cooling. One sometimes finds the sides of dikes glassy, while the interior is crystalline. The texture of glassy rocks is sometimes vesicular (Fig. 294) and sometimes pumiceous.

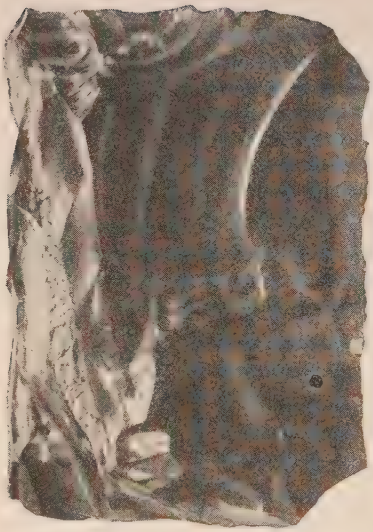


FIG. 327. — A hand specimen of obsidian, showing the characteristic conchoidal fracture. (U. S. National Museum.)

Obsidian or Volcanic Glass (Fig. 327) is pure, natural glass, entirely or nearly devoid of crystal grains. It is usually jet black in color, but is sometimes gray, green, red, or yellow. Because of the sharp edges which form when it is broken, it was highly prized by the Mexicans and other primitive peoples for the manufacture of sharp implements, such as knives and arrowheads.

Pitchstone is a variety of obsidian in which the luster is resinous or pitch-like. The chemical and other differences between this rock and obsidian are slight. Pitchstones are variable in color. When conspicuous crystals are scattered through the rock, it is called *pitchstone porphyry.*

FRAGMENTAL VOLCANIC ROCKS

Rocks formed from the material thrown out by volcanoes are included under this head and are made by the consolidation of dust, ashes (material the size of a shot), lapilli (the size of a nut), and bombs (pieces the size of an apple, or larger).

Tuff. — When the rock is composed entirely of the finer kinds of volcanic detritus, it is called *volcanic tuff.* Rocks of this type are light in weight and usually loose in texture, although some are almost as compact as felsites. Tuffs contain fossils if the dust and ashes of which they are composed fell on a land surface covered with vegetation, or in water in which marine organisms were living. Some of the rock through which the Panama Canal was cut is a tuff containing[1] marine shells. Tuffs are widely used in Mexico for building stones.

Volcanic Breccia. — This is a rock composed of angular fragments of volcanic rock, bombs, etc., which are cemented together with ash and dust.

---

[1] For a more detailed study of igneous rocks the student is referred to L. V. Pirsson, *Rocks and Rock-Minerals;* and J. F. Kemp, *Handbook of Rocks.*

FIG. 328. — Basaltic columns in a lava flow near the city of Mexico.

Columnar Structure of Lava. — A striking feature of many ancient lava flows whose lower portions have been exposed to observation by erosion is their columnar structure, the lava being broken up into angular columns which are often six-sided. If the lava sheet is horizontal, the columns are vertical (Fig. 328); if it has been intruded into a fissure (dikes), the columns are horizontal (Fig. 329). One may observe similar joints in dried mud and starch, but in these substances the sides are much less regular. The explanation of columnar jointing is to be found in the contraction of the lava, resulting from cooling and loss of gas, and the consequent cracking of the rock. Since the least expenditure of energy is required to relieve the strain when three cracks radiate from equidistant points at angles of 120°, the formation of six-sided

FIG. 329. — A dike (depressed) showing the basaltic jointing at right angles to the walls. Maine. (Photo. F. Bascom.)

columns usually results, and the direction of the columns is at right angles to the cooling surface. The reason for the horizontal position of the columns of vertical dikes and the vertical position of those of lava flows is thus explained (Fig. 330 *A–C*).

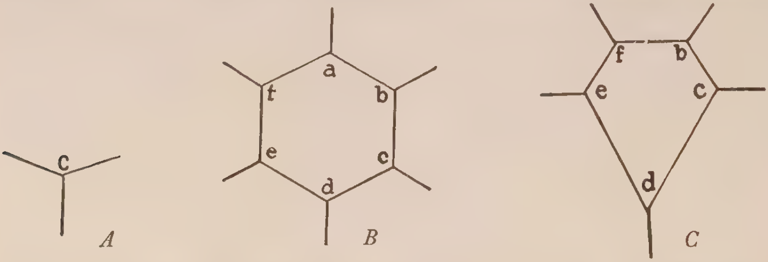


Fig. 330. — Diagrams showing the origin of basaltic jointing. In shrinking, the least number of cracks that will relieve the tension in all directions, *A*, is three. Similar radiating cracks from other centers complete the six-sided prism, *B*. When cracks fail to develop about some one point, a five-sided prism, *C*, results. (Modified after Chamberlin and Salisbury.)

AGE OF IGNEOUS ROCKS

The exact age of ancient volcanoes or of igneous intrusions can seldom be ascertained, but the relative age is often known. The relative age is determined as follows: a volcanic neck is clearly younger than the rocks which it penetrates; a laccolith or sill is of later age than the beds in which it was intruded, and a lava flow is more recent than the formations over which it spreads. The eruption or intrusion in each case could not have taken place before these rocks were laid down. If on the other hand pebbles of igneous rock are found in sedimentary rocks, we know that the rocks from which they were derived were at the surface before the sediments were deposited, or while the deposition was taking place. For example, if Devonian strata are cut by a volcanic neck, we know that the neck is younger than the Devonian, and if pebbles from this same neck are found in Middle Carboniferous sediments, it is evident that the lava was probably intruded in early Carboniferous times. Sometimes the presence of fossils in volcanic tuff shows definitely at what time the eruption occurred.

THEORIES OF VOLCANISM

So many theories of volcanism have been offered that it is impossible in an introductory volume to do more than briefly indicate a few of them. The theories may be classed under three heads: (I) those which assume a molten interior; (II) those based upon the assumption that the earth is solid from the surface to the center; (III) those holding that a few miles below the surface a zone of rock exists which is either molten, or at any rate in a non-crystalline condition.

I. Theory Based upon the Assumption that the Interior is Molten

The theory of a molten interior is now held by few geologists because of the many objections to it (p. 273). In the earlier days of geology when this theory had general acceptance, the difficulty of accounting for the independence of volcanic eruptions brought forth much discussion, and a number of modifications to the theory were suggested. If all lavas came from one great reservoir, it is evident that according to the law of hydrostatics eruptions would be simultaneous, or in two adjacent vents, from the lowest one.

II. Theories Based upon the Assumption that the Earth is Solid

(*a*) **Heat by Friction.** — This theory is based on the fact that heat is developed by friction when rocks grind and crush each other. It is held that when great earth blocks (segments) move past each other, the pressure and friction along the lines of movement develop heat on a large scale. If fluxes (rocks which upon uniting with others produce a substance that will melt readily) are present to lower the melting point of the rock silicates, the heat may be sufficient to produce molten rocks and volcanoes. Since all rocks contain more or less water, steam under immense pressure will be developed upon the fusion of the rock. Explosions of the steam developed in this way are believed to be competent to drill channels to the surface, and to eject the molten rock through the chimneys thus formed. The intermittent action and extinction of volcanoes, according to this theory, are dependent upon the movement of the earth's segments. It should be noted in this connection that no observations have been made of faults the walls of which are fused as a result of slipping.[1]

(*b*) **Formation of Lava Reservoirs by Relief of Pressure.** — This theory rests on the assumption that at moderate depths the heat of the earth is so great that the solid state of rocks is maintained only by the pressure of overlying rocks. If this assumption is correct, it is only necessary to show that the pressure of highly heated rocks can be relieved. This is thought by the advocates of the theory to be accomplished when deeply buried, sedimentary strata are folded. If a stratum strong enough to sustain the weight of the overlying rocks is arched, and the underlying rocks are thus relieved of some of the pressure, the latter may melt. A volcano or fissure eruption may then occur if a crack to the surface is present through which the lava can force its way. The supply of lava would depend upon the amount of molten rock under the arch, and the extinction of the volcano would result from its exhaustion.

Two strong objections to the theory are: (1) the difficulty of accounting for a temperature in sedimentary rocks high enough to fuse them, and (2) the difficulty of explaining the presence of sedimentary rocks of basaltic composition (p. 331) of sufficient thickness under an arch to be a source of the lava of massive plateaus.

[1] Schwartz, E. H. L., — *Causal Geology*, p. 241.

(*c*) **Liquid-thread Theory.**[1] — This theory assumes that the earth grew by the slow accession of meteorites (planetesimals), varying greatly in size and composition (p. 386), and that the interior, though solid, has become very hot as a result of the compression of the interior masses by the accumulation of the outer envelopes. In a globe composed of masses varying greatly in composition and fusibility, it is evident that some particles will be molten while others are still solid. As a result of the strains to which the earth is subjected, the liquid portions gradually move toward the surface, uniting in their upward course into larger and larger threads (Fig. 331). Because of their heat these threads finally reach the zone of fracture by fusing and fluxing. When such threads of liquid rock attain the zone of fracture, they take advantage of any fissures or fractures which exist, and are poured out on the surface as fissure or volcanic eruptions. The intermittency of volcanic action is due, according to this theory, to temporary deficiencies in the supply, and the force of expulsion is produced especially by tidal and other stresses and by the slow pressure brought to bear on the threads of liquid rock, until the upper level is reached, where the expansion of the occluded gases begins to operate.

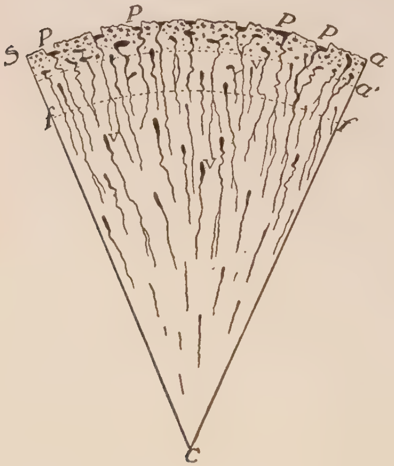


FIG. 331. — Diagram illustrating Chamberlin's theory of volcanism. *S* is the surface of the earth; *aa'*, the zone of fracture; *af*, zone of flow; *ffc*, interior portion whose temperature rises from the surface melting point at *ff* to a maximum at *c*; *vv*, threads or tongues of molten rock rising from the interior to various levels, many of these lodging within the zone of fracture as tongues, batholiths, etc. *PP* are explosive pits formed by volcanic gases derived from tongues of lava below. (After Chamberlin and Salisbury.)

This hypothesis, as has been pointed out, is based upon the assumption that the earth has never been in a molten condition, and that its interior is composed of a heterogeneous mass varying greatly in composition. If the observations upon which the following hypothesis (abyssal injection) is based are well-founded, — namely, that the crust of the earth is composed of acid (granitic) rock and that this is underlain by a basic (basaltic) substratum, — the hypothesis cannot stand, since the latter holds that the earth was formerly molten at the surface.

III. Abyssal Injection Hypothesis[2]

This hypothesis is based both upon laboratory experiments and upon many observations of the occurrence and relationships of igneous rocks in various parts of the world. It should be distinctly borne in mind, however, that the hypothesis is as yet unproved.

---

[1] Chamberlin and Salisbury, — *Geology*, 2d ed., Vol. 1, p. 629.

[2] Daly, R. A., — *The Nature of Volcanic Action*: Am. Academy of Arts and Sciences, Vol. 47, June, 1911, pp. 47–122; and *Igneous Rocks and their Origin*.

It assumes that there exists, at a depth estimated at 40 kilometers (about 23 miles), a basaltic (basic) substratum which underlies an almost universal shell of acid rock (granite, etc.). Because of the pressure of the overlying rocks, this substratum of actually or potentially fused rock is so rigid as to *act as a solid*. It holds that all igneous action is the result of the mechanical intrusion of the substratum basalt into the overlying crust. The intrusion of the magma is accomplished largely by "stoping"; that is, cracks in the overlying rocks are entered by the molten mass, blocks are wedged off and are ultimately absorbed in the magma. At the contact, solution takes place to some extent, but this is believed to be of secondary importance to stoping. The vent of the volcano or fissure for the last few hundred or thousand feet may have been opened by explosions or by fissuring. Once the movement of the molten magma is started, the original heat of the intrusion is maintained by chemical and exothermic reactions (the heat liberated in the formation of chemical compounds).

The explosiveness of volcanoes, according to this theory, is the result of the original gases of the molten rock, as well as of the water which the magma absorbs from the intruded rocks in its ascent. The cause of the extinction of volcanoes is shown in the diagram (Fig. 332). The active vent is situated at the highest point of the injected magma, and it is in this place that the gases of the magma accumulate. The temperature of the magma in such situations is believed to be not only that of its primal heat but also to be increased by chemical reactions and by other means connected with the presence of the gas. Vents become extinct when, because of the higher position of the magma in other locations, the gases which cause the fusion accumulate elsewhere. According to this theory, the composition of the lava ejected from a volcano depends upon whether it is composed entirely of the basaltic magma of the substratum, or is a mixture produced by the solution of the rock through which the basaltic magma has passed.

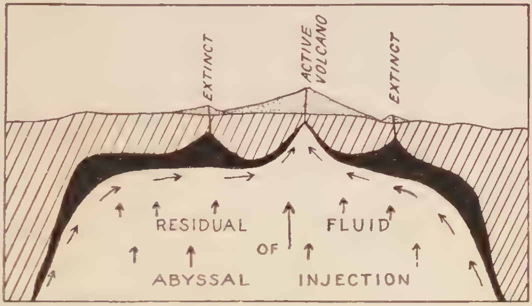


Fig. 332. — Ideal section illustrating the abyssal injection theory. The middle vent is active because it originates at the highest point in the injected body. The other vents are extinct because of the advantage of the middle vent. The arrows show the movement of the gas; the solid black, the crystallized portion of the injection.

Résumé of Present Knowledge of Volcanism

There is no agreement as to the origin of lava; (1) some investigators hold that a portion is derived from deeply buried sedimentary rocks which have a high temperature as a result of the rise of heat from the earth's interior, so that when the pressure of the overlying rocks is relieved, the more fusible strata liquefy; (2) some hold that it is formed as the result of heat produced by friction between great blocks of the earth, when the earth's crust is yielding to strains; (3) some, that it is chiefly or entirely primal, *i.e.*, derived from a substratum of unknown thickness. Of these, the last (3) seems to be more in accord with the known facts (p. 337) than the others.

The activity of a given volcano is usually independent of all others, as is shown in the history of Mauna Loa and Kilauea (p. 308), which, though forming one great mound of lava, erupt independently. On the other hand, eruptions of Pelée and Soufrière on the West Indian islands of Martinique and St. Vincent have been almost simultaneous.

Origin of Volcanic Gases. — The problem of the origin of gases and water vapor is to a large extent identical with that of the origin of lava. It has been proved by experiment that all rocks, even the most dense and most crystalline, contain large quantities of gas, so that a comparatively small volume of rock would be sufficient to furnish practically all of the gases and all of the water vapor given off during an eruption even of the first magnitude. It has been held, however, that water vapor, which constitutes the greater part of the emanations of dormant volcanoes, as has been stated, is derived, to a large extent at least, from either sea water or from meteoric water which has percolated down to the molten lava and been absorbed by it.

Cause of the Ascension of Lava. — Every theory of volcanism must account for the force which raises the lava to the surface of the earth and often throws it as fine dust thousands of feet into the air. There is general agreement that this force is to be found (1) in the tidal and other strains to which the earth is subjected; (2) in hydrostatic pressure resulting from the weight of the overlying rock; (3) in the enormous expansive force of the gases dissolved in the molten magma, whether original or derived from other sources; and (4) to some degree in the expansional energy of the injected mass.

Cause of Periodicity. — The lava which cools in the throat of a volcano is characteristically tough. Since the cones of explosive volcanoes are built of loose ash deposits of little strength, it is evident that if renewed activity were to result from an explosion alone, an opening would usually be made through the side of the mountain instead of through the crater. The latter is, however, usually the case. There must therefore be some preliminary weakening of the plug, and apparently the only cause for such weakening is to be found in the fluxing (Fig. 333) by intensely hot gas[1] from deep in the earth. When the plug has been formed, heat is developed beneath it by the compression of the gas, by chemical reaction, and by gas solution. After the plug is shortened by the melting away of its lower end in this intense heat, the gas pressure may become great enough to blow out the remaining part. After the explosion, the lava in the throat of the volcano again cools and a period of inactivity ensues. The cause of extinction is discussed on p. 337.

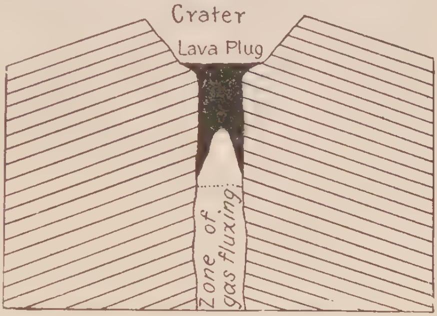


FIG. 333. — Section of a dormant volcano, showing how the lava plug may be weakened by gas fluxing. The broken line shows the original depth of the solid plug and the progress made by the gas. (Modified after Daly.)

In individual cases, as for example in that of Stromboli, eruptions occur when gas has accumulated under the scum of lava in the crater in sufficient volume to cause an eruption, after which quiet ensues, the surface of the lava hardens, and the gases again begin to accumulate.

Influences of the Atmosphere, etc. — Volcanic eruptions seem to be somewhat more prevalent when (1) the atmospheric pressure is high than when it is low, (2) after heavy rains rather than before, and (3) when tidal strains are unusually severe. None of these causes could produce an eruption, but it is probable that the increased weight of the atmosphere over a large area would aid in forcing out the lava, as would also the weight of the water after heavy rains. Tidal strains would have a similar effect. None of these agencies could be effective unless the eruption was imminent, only a slight additional force being necessary to start it.

It has long been noticed that the volcano Stromboli (p. 299) discharges a greater quantity of steam and bombs in stormy than in fine weather, and the fishermen make use of it as a "weatherglass": the increase of activity indicating a falling barometer and consequently stormy weather; and a diminution in activity promising fair weather.

---

[1] Such gases, called *primeval gases*, are believed to come directly from great depths and reach the surface for the first time. They are distinguished from *resurgent gases* which have a secondary origin, that is, those which are absorbed from the intruded rock.

REFERENCES FOR VOLCANOES

BONNEY, T. G., — *Volcanoes, their Structure and Significance.*
CHAMBERLIN AND SALISBURY, — *Geology*, Vol. 1.
DALY, R. A., — *Igneous Rocks and their Origin.*
DANA, J. D., — *Manual of Geology.*
GEIKIE, A., — *Textbook of Geology.*
GILBERT, G. K., — *Report on the Geology of the Henry Mountains*
HITCHCOCK, C. H., — *Hawaii and its Volcanoes.*
HULL, E., — *Volcanoes: Past and Present.*
IDDINGS, J. P., — *The Problems of Volcanism*
JUDD, J. W., — *Volcanoes.*
RUSSELL, I. C., — *Volcanoes of North America.*
SCHWARTZ, E. H. L., — *Causal Geology.*
SHALER, N. S., — *Aspects of the Earth*, pp. 50–56

TOPOGRAPHIC MAPS, U. S. GEOLOGICAL SURVEY, ILLUSTRATING IGNEOUS ACTIVITY

Volcanoes

Lassen Peak, California.
Crater Lake National Park (Special), Oregon.
Shasta, California.
Marysville Buttes, California.
San Francisco Mt., Arizona.
Island of Kauai, Hawaiian Islands.

Lava Sills

New York City and Vicinity (Folio).
Holyoke Folio, Massachusetts.
New Haven, Connecticut.

Laccoliths

Henry Mts., Utah.
Sturgis, South Dakota.

Lava Plains

Bisuka, Idaho.
Ellensburg, Washington.

CHAPTER X

METAMORPHISM

When either sedimentary or igneous rocks have been affected, either in their mineral composition or in their texture or in both, so that their original character is altered or entirely changed, they are called *metamorphic rocks*, and the process is known as *metamorphism* (Greek, *metamorphoun*, to transform or change). The term, as used here, will be limited to those changes which have resulted from heat or pressure, or both, whether produced locally, as for example by batholiths; or over large areas by pressure and heat.

Contact Metamorphism. — The form of metamorphism most easily understood is that produced when sedimentary rocks are cut by great igneous intrusions, such as batholiths. Under such condi-

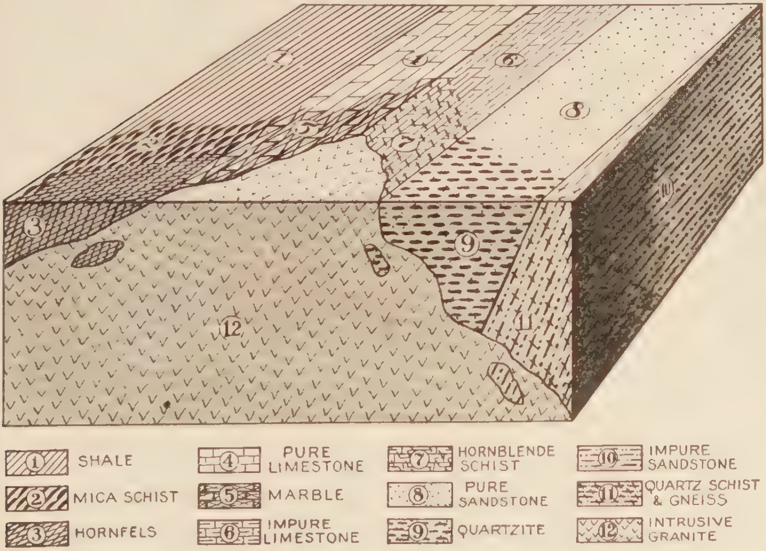


Fig. 334. — Diagram showing the metamorphism produced by a great igneous intrusion upon the surrounding rock.

tions, it is often found that the sedimentary rocks are greatly altered near the source of the heat (Figs. 334, 335). This is shown by a change in color, in hardness, and in texture, and in some cases by the development of new minerals. Bituminous coal is changed to anthracite coal, or even in the most extreme stage to graphite; limestone is metamorphosed to marble; soft sandstone may be converted into hard quartzite; and shale may be metamorphosed to dense, compact rocks, such as schist and hornfels, a compact flint-like rock. The amount and extent of contact metamorphism depends upon the amount of heat and to an important degree upon the gaseous emanations (mineralizers) given off by the molten rock. For example, if molten rock is intruded into a narrow fissure, the surrounding rock will usually be little affected (Fig. 336), since the magma, having a comparatively small amount of heat, soon loses it to the neighboring rocks. Moreover, the quantity of gas present is too small to produce a marked change. In the case of great intrusions, however, such as stocks or batholiths, the country rock may be greatly altered thousands of feet away. The effect of an intrusion is naturally greatest when the supply of heat is large and long-continued. In some cases, where fragments of the surrounding rock have been inclosed in the magma,[1] black shale has been baked to a hard, red, porcelain-like rock; granite has been more or less completely fused to dark green or black glass; and

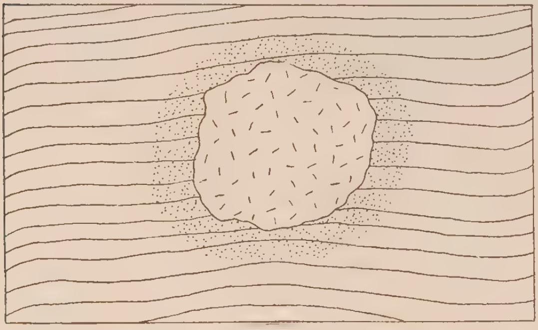


Fig. 335. — Map showing the metamorphic zone (dotted) about an igneous intrusion.

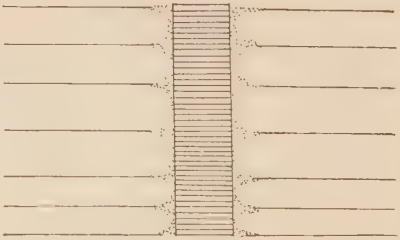


Fig. 336. — Diagram showing the greater metamorphic effect of an igneous intrusion along bedding planes.

---

[1] Powers, S., — *The Origin of the Inclusions in Dikes*, Jour. Geol., Vol. 23, 1915, pp. 1–10.

occasionally the fragments have been completely absorbed. The metamorphism resulting from intrusions is more extended when the intrusion cuts across strata than when it follows bedding planes, since under the former conditions the effect of the heat is felt along the several bedding planes with which the magma comes in contact (Fig. 336).

The metamorphic effect of an intrusion is greater than that of an extrusion, since in the former the heat of the magma is lost more slowly, and the neighboring rocks are consequently heated to a higher temperature and for a longer time. Moreover moisture, which is a powerful agent in metamorphism and in the production of crystalline structure in rocks, is more likely to be present under the former conditions. It frequently happens that the rock underlying a lava flow is so little metamorphosed that no change is visible to the naked eye.

The effect of great intrusions has already been discussed under Subjacent Masses (p. 327).

Regional Metamorphism. — Thousands of square miles of the earth's surface are underlain by metamorphic rocks. They underlie large areas in Canada, in the Adirondacks, in the greater part of New England, in the Piedmont region east of the Appalachian Mountains, in a large area south of Lake Superior, and in the Cordilleras.

Widespread or *regional* metamorphism may be brought about in one of two ways. (1) It may result from great *igneous intrusions*, such as deep-seated batholiths. (The metamorphism of the older rocks of the Laurentian region of Canada seems to have been produced largely in this way.) (2) *Great lateral pressure* may also produce sufficient heat to recrystallize the rocks affected. In regions where igneous intrusions are absent, as in New England, the metamorphism appears to have been caused by lateral pressure alone. The fact that the rocks of some metamorphic regions are more or less highly folded and that the intensity of the metamorphism is, to some degree, in direct proportion to the intensity of the deformation is offered as proof that the alteration of the rocks in such regions was due, either directly or indirectly, to the cause or causes which produced the folding. The indirect cause is believed to have been the pressure which produced the deformation; the direct causes, the heat resulting from the rock mashing produced by pressure, and the presence of underground water which aided powerfully in bringing about the molecular changes which resulted in the crystalline texture.

CLASSIFICATION OF METAMORPHIC ROCKS

Quartzite. — A quartzite is a *metamorphic sandstone.* It is a compact rock composed of grains of quartz sand cemented by material of the same kind, that is, by silica. It can usually be distinguished from sandstone by its appearance when broken. The broken surface of sandstone usually has a more or less granular feel and appearance, since the fracture takes place in the weak cement leaving the grains outstanding. In quartzite, on the other hand, since the grains and cement are of the same material, the fracture takes place in cement and grains alike. It is often difficult to state whether a quartzite owes its character to heat and pressure or to cementation by underground water. A *quartz schist* is a quartzite in which a foliated structure has been developed, the planes of foliation being covered with white mica.

Marble. — Commercially, any calcareous rock which will take a polish is called a *marble,* but in a more technical sense a marble is a *metamorphic limestone.* It is distinguished from limestone by its granular appearance (texture) and, unlike most metamorphic rocks, if pure is not schistose. When limestone is heated where the pressure is slight, it is converted into quicklime by the escape of carbon dioxide; but when heated under pressure, which prevents the escape of the gas, it crystallizes into marble. The clouded shadings and "veins" of marble are produced by the crystallization of impurities, with the resulting formation of colored minerals.

Slate. — This rock may be considered as a hardened shale or mud in which a tendency to break along parallel planes — not bedding planes — is developed. This condition is called *slaty cleavage* and by its means the rock splits readily into broad, thin sheets.

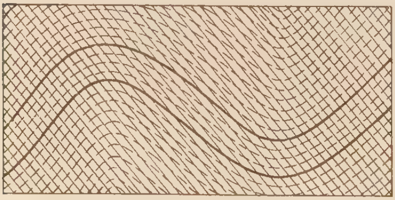


FIG. 337. — Slaty cleavage in folded rocks. (Modified after Pirsson.)

The *cause* of slaty cleavage is to be found in the great lateral pressure to which such fine-grained sediments as clay or (rarely) volcanic ash are subjected, especially if, when compressed in one direction, they are able to expand to some extent in others. A rock is affected by such compression in three ways: (1) any particles capable of compression are *flattened* and correspondingly lengthened at right angles to the pressure; (2) compression also *turns* elongated particles into parallel positions so that they take a direction in which their longest axes are at right angles to the pressure; (3) as a result of the metamorphism accompanying compression *new minerals*, such as mica, are formed, and since these crystals can grow more easily in the direction in which the pressure is least — along the line of least resistance — they also will have their longest axes at right angles to the pressure. The combined effect is to produce a rock which will cleave or split much more readily in one direction than in any other.

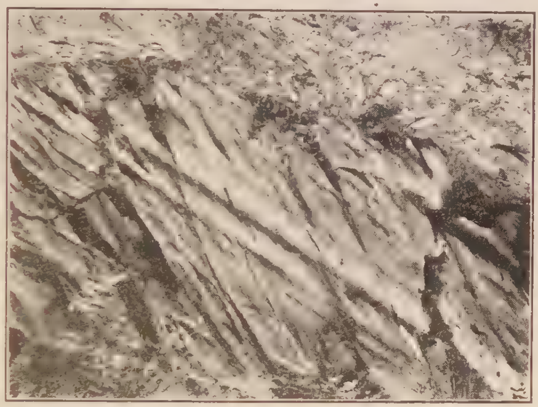


FIG. 338. — Illustration showing the relation of slaty cleavage (nearly vertical) to bedding (dipping to the right). (Photo. L. E. Westgate.)

Since a bed of shale is seldom perfectly homogeneous, slate differs in the perfection of its cleavage. Sandy layers, for example, are contorted and poorly cleaved, while the layers of pure clay have a perfect slaty cleavage. Slaty cleavage will be perpendicular to the bedding if the rocks were subjected to pressure when horizontal, but may be inclined at any angle to the bedding if the beds were folded before the pressure became intense (Figs. 337, 338).

The formation of slate requires much less extensive metamorphic changes than does that of schist and of gneiss (p. 346).

Schist. — Schists are rocks composed of thin, wavy leaves or folia in which the foliation (Latin, *foliatus*, leaved) or lamination is due to the abundance and parallel position of such minerals as mica, hornblende, or talc. The folia are not of uniform thickness, but are flattened lenses of the minerals, often bent and wavy, with their platy surfaces in parallel planes. The characteristic foliated structure of schists is developed when rocks have been subjected to great pressure. Schists are the result either of (1) the formation of new minerals which developed at right angles to the pressure, since growth takes place more readily along the lines of least resistance; or of (2) the deformation resulting from the crushing of such rocks as conglomerates, granites, or basalts. (3) In contact metamorphism the development of minerals, especially mica, along the stratification planes of sedimentary rocks also produces a schist.

Schists are given various names, depending upon their most conspicuous mineral. *Mica schist* is composed principally of mica and quartz and is the most common type of metamorphic rock. Mica schists are usually metamorphosed, fine-grained sandstones and shales. *Hornblende schist* consists largely of hornblende, and varies from green to black in color. In some cases, the characteristic needle or blade-like crystals are readily recognized, but in others the grain is so fine that the individual crystals cannot be seen. Hornblende schists are derived from diorites, gabbros, etc., by pressure, and it is probable that impure limestones containing sand, clay, and iron oxides also produce hornblende schists when subjected to metamorphism.

Fig. 339. — Gneiss, showing banding. (U. S. National Museum.)

Gneiss. — This is a banded, crystalline rock (Fig. 339) in which feldspar is present. It is a rock with the composition of granite, but with a banded structure. Gneiss may be considered for convenience as intermediate between an igneous rock, such as granite or diorite, and schist. It will readily be seen from the above that a gneiss may, on the one hand, so closely resemble a schist that one will be in doubt as to its classification, and on the other hand, that it may be confused with a granite. Typically, however, gneisses are easily recognizable and may be considered for convenience as *banded granites*. As in the case of schists, various qualifying adjectives are used in describing gneisses, as *biotite gneiss*, *hornblende gneiss*, *garnet biotite* *gneiss.* Gneisses may be formed either (1) by the metamorphism by mashing of granite or other igneous rock; (2) by the metamorphism of sedimentary beds; or (3) when a granite magma is intruded into sedimentary or schistose beds under great pressure, the molten magma being forced along the sedimentary planes or between the folia of the schists. This intimate admixture permits of extensive mineral changes, and the two types of rock, very different in geological age, become welded into a *composite gneiss.*

TABLE SHOWING METAMORPHIC CHANGES

SEDIMENTS	SEDIMENTARY ROCKS	METAMORPHIC EQUIVALENTS
Gravel	Conglomerate	Gneiss and various schists
Sand	Sandstone	Quartzite and quartz schist if from pure quartz sand; mica schist if certain impurities are present
Clay	Shale	Slate and schists, especially mica schist
Lime deposits, such as chalk or shells	Limestone	Marble

IGNEOUS ROCKS	METAMORPHIC EQUIVALENTS
Granite, syenite, and other rocks with much feldspar	Gneiss
Fine-grained feldspar rocks, such as felsite and tuffs	Slate and schists
Diorite, basalt, and other basic rocks	Hornblende schist and other schists

SUMMARY OF CAUSES OF METAMORPHISM

The important factors to be considered in the production of metamorphism are heat, moisture and pressure, mechanical movements, and the nature of the material involved.

Heat. — The heat necessary for metamorphism may come (1) from igneous intrusions. In this way the surrounding rocks are hardened and dehydrated. The process is shown in the manufacture of bricks, in which the clay is dehydrated and is hardened to a rock-like mass by partial fusion. New minerals are often developed in rocks affected by intrusions. (2) The heat developed by pressure will be discussed in a later paragraph.

Moisture. — When moisture is present in considerable quantity, as is the case with sedimentary rocks, the effects of heat and pressure in producing metamorphic changes are greatly increased. This is true because highly heated water, especially if alkalies are present, readily dissolves minerals which would otherwise be insoluble, and from the solution the same minerals or new ones may be formed. Water also takes part in the chemical composition of some minerals, such as mica, and is therefore necessary for their formation. The recrystallized and newly formed minerals are usually arranged with their longer axes at right angles to the pressure (p. 349), and are more stable under the new conditions than if they had not been changed. The potency of moisture is shown by the fact that rock which requires a temperature of 2500° F. for melting when dry, becomes pasty at 750° F. when water is present. The effect of gaseous emanations in producing metamorphism is sometimes of the greatest importance.

Pressure. — Simple downward pressure, such as that which results from the weight of overlying rocks, has some metamorphic effect and also tends to consolidate the sediments by bringing the grains closer together. But when the crust is under enormous lateral pressure, as a result of the contraction of the earth, the strata are folded, crushed, and mashed together, and metamorphism takes place. In this way pebbles, fossils, and crystals are flattened and elongated, or broken into fragments. By this agent alone the texture of rocks can be changed, but it is in combination with heat and moisture that the production of new minerals and the formation of highly metamorphic rock is brought about.

The importance of lateral pressure in the production of regional metamorphism has been questioned by certain French geologists[1] who believe that it is brought about by heat, moisture, and vertical pressure without the aid of lateral pressure; that the sediments in the lower parts of thick geosynclines are actually fused by heat from the interior of the earth, and upon cooling become igneous rocks, capable in their turn of metamorphosing by contact the rocks which surround them. They hold that this is by far the most important element in the process of metamorphism and that dynamic action can deform but cannot transform rock; *i.e.*, it is not competent by itself to produce metamorphic changes. This theory has been generally abandoned by American geologists and in fact by many eminent French geologists.

How the Parallel Arrangement of Minerals is Produced. — The conditions favorable for the production of metamorphism having

---

[1] Haug, — *Traité de Géologie*, pp. 172–191; 234–235.

been discussed, it remains to be shown why metamorphic rocks are usually cleavable.

1. **Crystallization.** — A study of a mica or hornblende schist shows that hornblende and mica are responsible for the best rock cleavage. A microscopic examination of these rocks and of the sedimentary rocks from which they were derived shows that hornblende and mica were built up chiefly by subsequent recrystallization from substances already in the sedimentary rocks and did not exist in them in their final form. This fact is shown by a general lack of fractures in the minerals of the cleavable rock, such as would have been developed had the rock been formed simply by crushing and by the rotation of the mineral constituents to parallel positions. Moreover, most of the mineral particles of cleavable rocks are larger than those of the same rock before the latter was metamorphosed. The gradation of shale to phyllite (a metamorphic shale) means an increase in the size of the grains. The parallel arrangement of the mineral constituents of a metamorphic rock is thus seen to be the result of crystallization, and the rotation of the original particles to a parallel position, of minor importance.

2. **Granulation.** — Recrystallization and rotation are not the only processes instrumental in the production of easy splitting or cleavage in metamorphic rocks. In the early stages of the process the larger brittle particles are broken into small fragments or are *granulated* and elongated, and at the same time recrystallization builds up new minerals from the broken particles.[1] It is probable that granulation aids crystallization in that it grinds the particles into small pieces which then present a greater surface upon which the chemical process may act.

Relation of Cleavage to Pressure. — The proof that the planes of easy splitting of metamorphic rocks are at right angles to the pressure, or in other words parallel to the rock elongation, is seen (1) in the distortion of the pebbles of conglomerates, (2) in the distortion of fossils, the lengthening being in the plane of the cleavage, and (3) when rock is intruded by igneous masses which exert a great pressure on the walls, in the cleavage which is developed parallel to the walls.

From Igneous, through Sedimentary, to Metamorphic Rocks. — The history of a metamorphic rock, formed by the recrystallization of sedimentary rocks, may be briefly summarized. If a great mass of granite is exposed to the weather, it begins to decay; its feldspar

[1] Leith, C. K., — *Structural Geology*, 1913.

and mica being disintegrated and forming simpler compounds, some of which are dissolved and carried away by the water, while the remainder is left as clay. This clay together with the insoluble quartz is transported by streams and is finally deposited in the ocean, the clay forming mud and the quartz grains, sand. The lime dissolved from the feldspars may be taken up by organisms to form lime ooze or limestone. If these sediments are laid down in a sinking geosyncline (p. 359), they may in time be buried to a depth of several thousand feet. When in the course of their burial they reach the belt of cementation (p. 61), they will be consolidated into shales and limestones. If the sediments in the syncline are subjected to great lateral pressure, heat will be developed which will metamorphose them, changing the clays, sandstones, and limestones to schists, quartzites, and marbles.

For a discussion of the formation of metamorphic rocks from igneous rocks, see p. 347.

Weathering of Metamorphic Rocks. — Metamorphic rocks *usually* resist weathering better than sedimentary ones, because they have been compacted by heat and pressure and have a crystalline texture. Mica schist, for example, is less easily disintegrated than the impure shale from which it was made; hard quartzite than the less compact sandstone; marble, however, may or may not be more resistant to weathering and erosion than the limestone from which it was derived; the disintegration of slate is hastened by its vertical cleavage, but is hindered by its greater compactness. As a result of prolonged weathering, however, metamorphic sedimentary rocks are reduced, in time, to the same soil which their sedimentary equivalents would have made, schists weathering to clays; quartzites to sands; and marbles to calcareous clays. Because of their greater resistance to weathering, metamorphic rocks are usually associated with the scenery of mountains. Quartzite usually resists weathering better than any other rock on account of its small porosity, its insolubility, and its homogeneous composition. Because of the last-named character, it is little affected by changes in daily temperature (p. 31), and it is not disintegrated by the decay of a weaker constituent, as is the case with igneous rocks, such as granite. Quartzite hills are, consequently, among the last to disappear. In regions of metamorphic rocks, where schist and marbles are involved, streams have usually cut their valleys in the softer and more soluble marbles, while the more resistant schists form hills and mountains.

Economic Importance. — Gneisses and quartzites are often used for building stones and road material, but marble is the metamorphic rock which is the most prized, both for building purposes and for works of art.

REFERENCES FOR METAMORPHISM

Chamberlin and Salisbury, — *Geology*, 2d ed., Vol. 1, pp. 426–449.
Cole, G. A. J., — *Rocks and their Origins*.
Leith, C. K., — *Structural Geology*.
Pirsson, L. V., — *Rocks and Rock-Minerals*.

634

CHAPTER XI

MOUNTAINS AND PLATEAUS

THE term *mountain* is used very loosely to indicate a conspicuous height of land. In flat regions such as southern New Jersey and the plains of Texas, heights rising more than 100 to 200 feet are dignified by the name mountain, while in mountainous regions elevations of 1000 or 2000 feet are often called hills. It is evident that the term is a relative one, since on plateaus a mile or two above the sea a conspicuous elevation must be still higher, and a mountain in such a situation would be at least 6000 feet above sea level. A *mountain ridge* or *range* is usually long, with a narrow crest; when numerous ranges are associated, they constitute a *mountain chain.* In ancient paintings and in old geographies, the slope of mountains was usually depicted as very steep, an angle of 60° from the horizontal not being uncommon, but such slopes seldom occur in nature, and angles as high as 35° are rare.

Mountains of Accumulation.—Volcanoes are typical of this class, as they are built up by the accumulation of ash, or lava, or both. They sometimes occur singly, sometimes they are arranged along fracture lines (p. 267), and sometimes no definite order can be recognized.

Since sand dunes (p. 52) occasionally attain a height of 600 feet and moraines (p. 159) a height of 1000 feet, they are sometimes called mountains in regions where other elevations are inconspicuous and must therefore be included under the head of accumulation mountains.

Residual Mountains.—These are formed when a plateau has been extensively dissected by rivers, and the ridges and pyramids, the remnants of the plateau, which have escaped erosion, stand so high above the valleys as to constitute mountains. The many "temples" in the Grand Canyon of the Colorado in Arizona (Fig. 340) show at a glance how such mountains are formed, and the Catskills of New York furnish an excellent example of residual

FIG. 340. — A "temple" in the Grand Canyon of the Colorado, Arizona, showing how residual mountains are formed. (U. S. Geol. Surv.)

mountains in which gentle slopes are characteristic. The form of mountains of this class depends upon the nature and arrangement of the material (Fig. 340) out of which they were sculptured, and to some extent upon the climate. The Catskills owe their gentle slopes to the fact that the rocks of which they are composed do not differ greatly in hardness, and also to the smoothing effect of a moist climate. The steep-sided mesas of the southwestern United States are often the result of the erosion of lava plateaus, the hard lava forming flat-topped mountains bounded by conspicuous, vertical cliffs. Residual mountains are confined to those formed of horizontal rocks or slightly inclined rocks. The external form of *complexly folded* mountains (p. 356) is due to erosion, and they are in a sense residual mountains. They have, however, been placed in a class by themselves because of the origin of the folded structure which gives them a distinct character.

Fault or Block Mountains. — It was shown in the study of faulting (p. 267, Fig. 266) that important topographic features are produced in this way, and that mountain ridges of this origin have been formed either by uplift along one side of a fault, or by sinking along one side, or by a combination of the two movements. Mountains formed by the elevation of wedge-shaped blocks are called *horsts* (p. 263, Fig. 257). In southern Utah and Oregon *block* or *faulted mountains* have been carefully studied and have been found to exhibit all the stages from young faulted mountains, in which erosion has as yet been able to accomplish little, to ancient fault mountains, in which erosion has proceeded so far that their origin can merely be conjectured. In portions of these regions block mountains 10 to 40 miles long and 1000 to 1200 feet high occur. The ridges are steep or cliff-like on the fault side and have a gentle slope on the opposite side. Between the faults are trough-like depressions in which lakes sometimes rest. The steep eastern slope of the Sierra Nevada Mountains marks the fault along which a great block, 500 miles in length and 70 to 100 miles broad, has been raised, the escarpment thus formed rising from 5000 to 6000 feet above the desert valleys to the eastward, and reaching a maximum height of 14,000 feet in the vicinity of Death Valley. (Russell.) Well-known examples of block mountains are the Vosges and Black Forest of Germany (p. 100, Fig. 81).

Laccolith Mountains. — Under the discussion of laccoliths (p. 327) it was seen that in certain localities molten material has been injected into the earth's crust in such quantity that the cover of sedimentary strata has been lifted into dome-like forms. After prolonged erosion the softer strata are partially or wholly removed, and the hard, igneous core is left as a mountain or hill. In mountains of this origin, the strata dip away in all directions from the center, and not uncommonly "hogbacks," with steep cliffs facing towards the center, form one or more broken rings about the mountain. Although mountains of this type are not abundant, a large number are known to exist, of which those in Utah, California, Wyoming, South Dakota, British Columbia, and Canada might be mentioned (Fig. 341).

FIG. 341. — Little Sundance Dome, Sundance, Wyoming. This is a laccolith from which the overlying strata have been eroded.

Domed Mountains. — The Black Hills of South Dakota may be taken as a type of domed mountains. They rise 2000 to 3000 feet above the surrounding plains and about 7000 feet above sea level, and are carved from a dome-shaped uplift of the earth's crust. The length of the dome is about 100 miles and the width about 50 miles, — about the size of Connecticut. As will be seen from the diagram (Fig. 342), the eroded central part is composed of crystalline rocks from which the strata dip in all directions. As a result of the more rapid erosion of a stratum of shale, a trench called the Red Valley, in many places two miles wide, entirely surrounds the center, except where it is cut through by streams. The Red Valley is separated from the flat plains surrounding the central mountain mass by a rim or "hogback," which presents a steep face towards the valley and rises several hundred feet above it.

The Uinta Mountains of Utah are formed from a flattened dome or broad arch 150 miles long and 20 to 25 miles wide, which rises about 10,000 feet above sea level. It will be seen from the diagram (Fig. 343) that if all the rock which has been carried away were restored, the mountains would be three and a half miles higher than now. This does not prove that the mountains were ever as high as that, since the denudation of a mountain mass commences as soon as it begins to rise above the surrounding country, and the rate of erosion in all probability is about the same as the rate of upheaval.

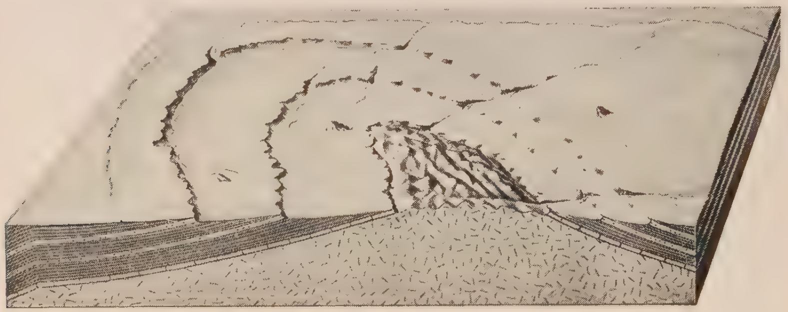


Fig. 342. — A block diagram of a domed mountain, the Black Hills of South Dakota. The investing valleys with their steep, infacing cliffs are well shown. The central mountain mass is granite, and the three isolated mountains are intrusive masses of igneous rocks.

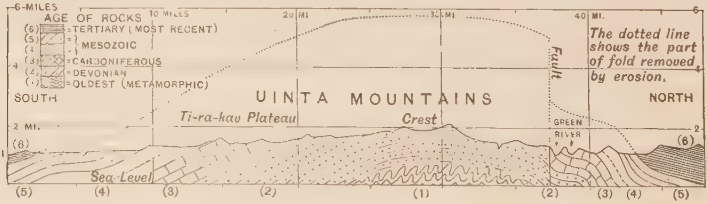


Fig. 343. — A section across the Uinta Mountains, Utah. The range has been formed out of a single broad arch 40 miles wide, which has been greatly eroded. The original surface is indicated by the dotted line, showing that three and one half miles of rock have been removed by erosion.

Complexly Folded Mountains. — It is to this class that the great mountain systems of the world belong, the Appalachians, the American Cordilleras (the Rocky, Sierra Nevada, Coast, and Cascade mountains), the Alps, Himalayas, Pyrenees, etc. The strata which compose them may consist of a series of gentle anticlines and synclines (p. 254), or may be intricately folded and faulted. Portions of the Jura

Mountains of Switzerland present a classic example of gently folded strata; here one finds, in certain places across the system, a series of simple anticlines and synclines (Fig. 344). A portion of the Appalachian Mountains in Pennsylvania also presents a similar simple structure (Fig. 345). In the Alps, however, the folds are much more pronounced and complicated, and it is often extremely difficult to determine the structure of the strata (Fig. 346).

Fig. 344. — Section through the Juras, showing mountain ridges produced by several open folds, like great earth waves.

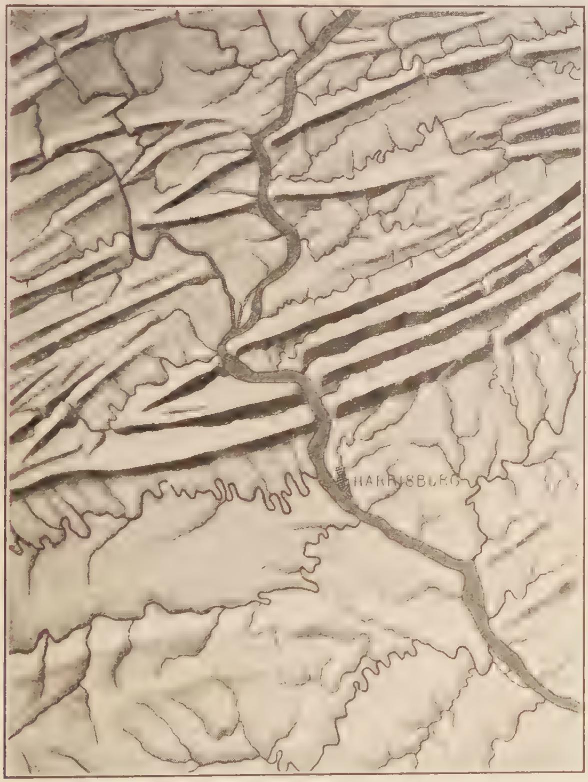


Fig. 345. — Relief map of the Appalachian Mountains. (See Figs. 244 and 245, p. 255.)

It is evident that a series of strata, subjected to forces sufficient to produce the intense folding shown in the Alps and in the southern Appalachians (Fig. 347), will often break and fault instead of folding. It is, consequently, seldom that folded strata are free from dislocations over a distance of even a few miles. The strata of folded mountains have often been so compressed that cleavage planes parallel to the folds have been induced. Metamorphism is in proportion to the intensity of the compression.

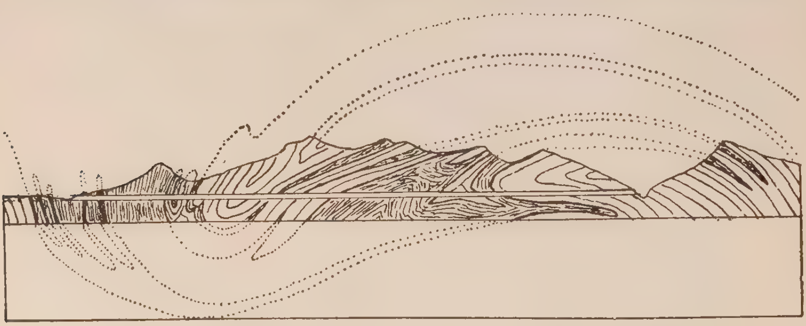


Fig. 346. — Diagram showing a cross section of the Alps along the Simplon tunnel. The complicated structure and former extension of the strata are shown. (After Schmidt.)

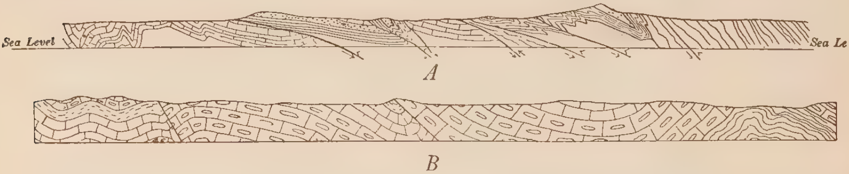


Fig. 347. — *A*, section across the southern Appalachians where extreme faulting has occurred (U. S. Geol. Surv.); *B*, section in the vicinity of Chattanooga, Tennessee.

Origin and Development of Folded Mountains

Four points have been established with reference to folded mountains: (1) they were formed from thick sediments that had accumulated in geosynclines; (2) they were folded as a result of lateral pressure; (3) the rate of folding was slow; and (4) their outlines, after prolonged erosion, are determined largely by the character of the rocks and the arrangement of the strata. A discussion of these points follows.

There is also reason to believe that mountains of this class are situated at the junction of great earth segments or blocks where, as a result of the crowding of the latter upon each other as they are drawn toward the center of the earth, the weak strata of geosynclines are folded.

1. **Geosynclines.** — The sedimentary strata of which folded mountains are formed are very thick; in the Appalachians, the thickness is about 25,000 feet; in the Coast Ranges of California, 30,000 feet; and in the Alps, 50,000 feet. When a stratum is traced to a distance of even a few miles from the mountain chain, it is found that it rapidly becomes thinner; the strata that have a thickness of about 25,000 feet in the Appalachians, for example, are only about 2500 feet thick in the Mississippi Valley. An examination of the rocks of mountain masses often shows that many of them are of shallow water origin, as the occurrence of conglomerates and sandstones testifies. Ripple marks, sun cracks, and fossils afford similar evidence. The presence of limestones, on the other hand, may indicate (p. 238) that the water in which they were deposited was deep or far from shore. The sediments that are being laid down in the seas to-day are deposited in a belt extending from the shore line to a distance usually considerably less than 50 miles (p. 237). Since there is no reason to believe that the conditions of sedimentation in the past were markedly different from those of the present, it is generally held that the strata composing the great mountain ranges were laid down near shore and, since many of them are of shallow water origin, that sinking accompanied and for the most part kept pace with the deposition, the land rising as the geosyncline sank. Occasionally unconformities occur, which indicate, as has been seen (p. 270), that elevation for a time interrupted the deposit of sediment.

2. **Lateral Pressure.** — When sediments have accumulated in a geosyncline to a depth of several thousand feet, those near the bottom of the deposit are somewhat weakened by heat (p. 347), so that they are compressed and thrown into folds when subjected to great lateral pressure. The strata composing the Appalachian Mountains of Pennsylvania, between Harrisburg and Tyrone (Fig. 348), were compressed from a width of 81 miles to one of 66 miles; *i.e.*, the earth's superficial crust, upon being folded, was shortened 15 miles, with a resulting mean elevation of three miles. It has been estimated that, if the folds of the Alps were smoothed out, the strata would cover an area 74 miles wider than the mountains do now, or about twice their present width. The shortening of the Front Range in

Colorado is estimated to be about 25 miles, and that of the Coast Ranges of California, 9 to 12 miles (Fig. 349).

A careful study of folded regions shows that the strata are often broken and faulted, the folds frequently giving place to thrust or reverse faults, especially where the strong or competent stratum is not deeply buried. As already stated in the discussion of reverse faults (p. 263), the overriding of the strata is sometimes 10 or more miles. In fact, in the southern Appalachians thrust faults are so numerous as largely to determine the positions of the mountain ridges (Fig. 347, p. 358), and the elevation in the Scottish and Scandinavian Highlands is due, to some degree, to the fault slices piled one on top of another.

Fig. 348. — Folds in the Appalachian Mountains between Harrisburg and Tyrone. (As restored by R. T. Chamberlin.)

Fig. 349. — Profile of the Santa Cruz Mountains in the Coast Ranges of southern California. (Arnold.)

Igneous rock is often associated with mountains and in some ranges is an important factor in the folding and metamorphism of the strata. It often composes the cores of mountain ranges and frequently forms their highest portions (p. 355). (1) The igneous core of mountain masses is often derived from igneous intrusions; (2) it may be the rock of the floor of the geosynclines; or (3) it has even been suggested that it is sometimes the lower portion of the sediments of the geosyncline which have been fused as a result of the rise of temperature (p. 348) from the interior of the earth. (Haug.) In each of these cases the igneous core is exposed only after erosion has removed a great thickness of overlying sedimentary rock.

Experiments in Mountain Building. — Experiments have been performed to determine whether the folds and reverse faults observed in such mountains as the Appalachians can be reproduced. In these experiments a series of layers composed of wax and other substances varying in rigidity and elasticity were prepared to represent rock strata of widely different character, such as shale, sandstone, and limestone. A load of shot, representing the weight of the overlying strata, was then placed on top of the layers. Upon the application of lateral pressure it was found that, by varying the rigidity and thickness of individual layers and of the layers as a whole, the phenomena observed in folded regions were reproduced. A study of the apparatus (Fig. 350) gives a better idea of the conditions of the experiment than a written description.

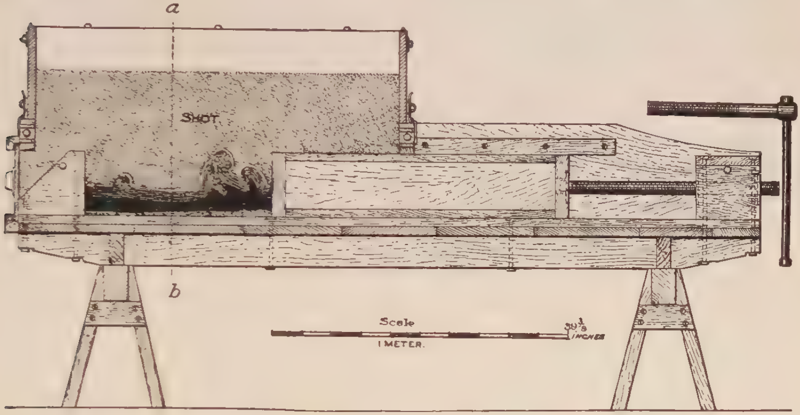


FIG. 350. — Machine for experimenting in mountains of folded structure. (U. S. Geol. Surv.)

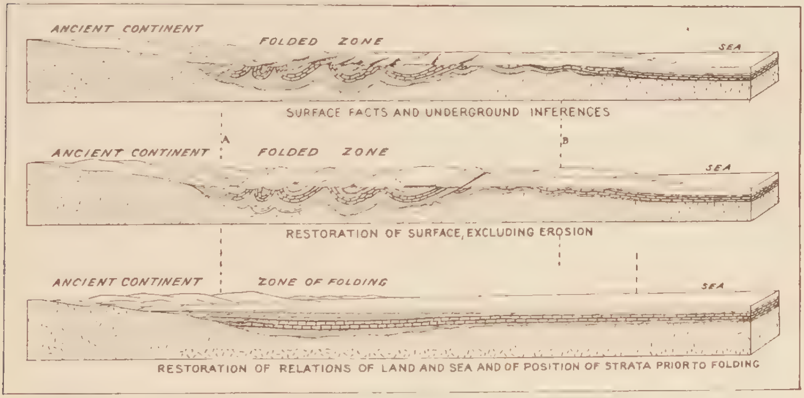


FIG. 351. — Diagrams showing the theoretical history of a folded region. The lowest figure shows the region when the present site of the mountains was a great geosyncline in which a load of sediment, 25,000 to 40,000 feet thick, had been laid down. The middle figure shows the region after it had yielded to great lateral pressure and had been folded and faulted. The upper figure shows the region as it is to-day. (Redrawn after Willis.)

A brief and incomplete history of a folded region is shown in Figure 351. It is incomplete because many of the important chapters of the history cannot be shown without too great confusion of detail.

3. **Rate of Folding.** — The rate of folding must necessarily differ widely in different geosynclines and in the same geosyncline at various times. In certain cases it seems to be proved that rivers have been able to deepen their valleys as rapidly as the land surface was elevated (antecedent rivers, p. 102). It is possible that the general denudation of a region may in some cases have proceeded at about the same rate as the elevation, so that at no time was the surface far above sea level. This may, for example, have been true of the Appalachians, which now consist of comparatively low mountain ridges although three or more miles of sediment have been removed by erosion; and also of the folded and crumpled rocks of New England (Fig. 352).

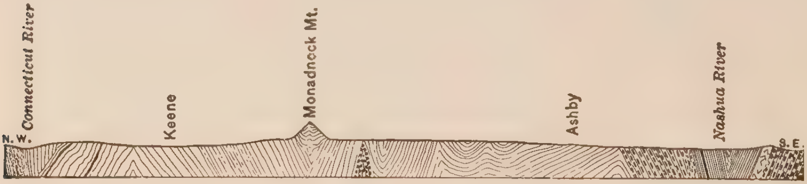


FIG. 352. — Section across central New England, showing the uplifted peneplain and Mt. Monadnock. (Hitchcock.)

The elevation of regions of folding was not always continuous, but, as is shown by a study of the Appalachians, the folded belts were at times above sea level and suffered erosion; upon being again depressed they received more sediment, unconformities marking the sites of the ancient erosion surfaces; and later, they were further folded and faulted and raised above the sea. The present height of the Appalachians and Sierra Nevadas was brought about by vertical elevation and not by lateral compression.

4. **To What the Topographic Features of Folded Mountains are Due.** — A comparison of the external form of mountains and their geological structure shows that the two seldom agree. It is true that the mountain ranges in general are parallel to the strike (p. 353) of the strata, but the valleys seldom coincide with the synclines and the ridges with the anticlines. This coincidence sometimes occurs, but the reverse is as frequently seen. In the Jura Mountains, Switzerland, excellent examples of synclinal valleys may be seen

(Fig. 344, p. 357), but in the Appalachians anticlinal valleys are perhaps more common than synclinal ones. This lack of coincidence is due to the fact that when strata are folded the crests of the anticlines are stretched and consequently weakened, while the synclines are correspondingly compressed and strengthened. Moreover, when the land surface emerges from the sea, the crests of the anticlines are first attacked by erosion, and their strata may be worn through while the synclines are receiving sediment and are thus being protected. It is conceivable that a syncline may never have contained a stream, since before its surface was elevated above the sea, valleys had already been established in the anticlines.

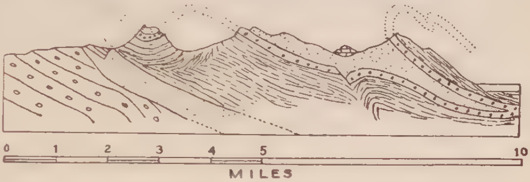


FIG. 353. — The slopes of the sides of the mountains are determined largely by the dip of the rock forming them.

If we imagine a number of folds, the anticlines and synclines of which are exposed to erosion at the same time, it will readily be seen that erosion will develop valleys in the anticlines, as it is now doing in the Jura Mountains. In intensely folded mountains where overturned folds occur, as is so frequently seen in the Alps, the variable character of the strata determines the cliffs and escarpments of the mountains (Figs. 353, 354). The gentle slopes of mountains of this structure are most likely to be found along the dip of the strata, the cliffs along the strike.

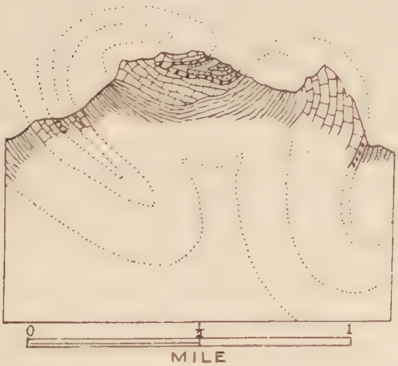


FIG. 354. — Section showing the effect of the dip of a resistant stratum upon the topography of a mountain.

The effect of a resistant stratum in determining the topography of a region is well shown in portions of the Appalachian Mountains, where a single sandstone stratum forms long mountain ridges wherever it outcrops at the surface. The *canoe valleys* of the Appalachians and other folded mountains are formed by the erosion of the strata of plunging anticlines (Figs. 244, 245, p. 255).

Cycle of Erosion of Mountains. — In the process of time mountains may be wholly reduced by erosion, and plains and plateaus be formed in their place, which will have all the structural features of folded mountains. Examples of such plateaus are to be found in the Piedmont of Virginia, in New England, and elsewhere.

In moist, tropical regions the luxuriant vegetation checks erosion, with the result that the forms are less diversified than in other areas.

Theories of Mountain Building

Mountain chains are more conspicuous than plateaus because of their narrow crests and great length in proportion to their width, but when the heights of mountains and plateaus are compared, it is found that many mountain ranges are relatively low as compared with many plateaus. Portions of the Appalachian Mountains, for example, are lower than portions of the Allegheny plateau only a few miles away. The Tibet plateau is 15,000 to 16,000 feet high, being higher than many of the great mountain chains of the world. The highest of the Colorado plateaus (Aquarius) is 11,600 feet, and that at Grand Canyon, Arizona, is 6000 to 8000 feet above the sea. It is evident from the above that the cause of the elevation of the less conspicuous but more massive plateaus is as important as that of the more spectacular mountains.

Cause of Lateral Pressure. — In the discussion of the interior of the earth it was pointed out that the earth is composed of a hot but solid core with a cool crust. The answer to the question, "What produces lateral pressure?" will be found to depend, to some degree, upon this relation.

The explanation often given for the crumpling of the earth's crust is that, as the interior heat is lost very slowly by conduction, the crust wrinkles to accommodate itself to the smaller interior. The comparison usually made is that of an apple which has been left in a warm, dry room. Under these conditions the interior of the fruit loses water by evaporation, while the dense skin shrinks but little and is wrinkled on the contracted interior. The efficacy of this cause has been proved impossible on the ground that the shrinkage of the interior of the earth has not been sufficient to produce the lateral compression seen in the great folded tracts of the earth's surface, and in proof of this contention it is pointed out that during a single era of the earth's history (Paleozoic, p. 477) the folding of the earth's crust resulted in a shortening of between 100 and 200 miles. Since a *lateral shortening* of six miles of the crust is produced by one mile of *radial shortening*, it follows that a minimum estimate would require a radial shortening of 16 miles, and a maximum, one of 32 miles.

The cause of the great deformations, such as those recorded in the Alps, the Appalachians, and other ranges, is believed to be found in the distribution of heat beneath the surface. It is thought that the heat of the interior " would be conducted from the deep interior to the outer zone 800 to 1200 miles thick, faster than from the latter outward, with the result of raising the temperature of the outer zone while that of the deep interior falls. The result of this should be a severe crowding of the outer zone upon itself, in shrinking to fit the deep interior as it loses heat and shrinks." (Chamberlin and Salisbury.) The folding of great areas therefore results, according to this theory, from the crowding of the thick outer zone on itself.

The extrusion of lava from the deeper zones of the earth coöperates with the cooling of the heated interior in causing a shrinkage. The outpouring of the hundreds of thousands of square miles of lava in Oregon and neighboring states, and in the Deccan peninsula of Asia, undoubtedly contributed to the shrinkage of the interior, although the total effect was slight.

The Elevation of Plateaus and Mountains. — The statement is often made that great mountain ranges are formed solely as a result of lateral pressure and also, when a region only a few hundred feet above sea level is found to be underlain by much folded and metamorphosed rocks, that "erosion has laid bare the mountains to their roots and that the ancient heights may at one time have rivaled the Alps in majesty." Such assumptions must, however, be accepted with caution. It seems safe, at least, to assume that, if great areas of the earth's surface can be raised by *vertical* movements to form plateaus, the elevation of a folded region may be largely due to similar *vertical* movements. This brings us to the modern theory of *isostasy* (Greek, *isos*, equal, and *stasis*, standing still).

The Theory of Isostasy.[1] — If oil and water are balanced in a U-tube, it is evident that, since water is the heavier, its surface will be lower than that of the lighter oil. It is upon this principle that the theory of *isostasy* is based. The ocean basins are believed to be underlain by heavier materials than the continents and are consequently lower, since they are drawn more strongly toward the center

---

[1] Hayford, J. F., — *The Figure of the Earth and Isostasy from Measurements in the United States:* U. S. Coast and Geodetic Surv., 1909.

Hayford, J. F., — *The Effect of Topography and Isostatic Compensation upon the Intensity of Gravity:* Special Publication 10, U. S. Coast and Geodetic Surv., 1912.

Reid, H. F., — *Isostasy and Mountain Ranges*, Bull. Am. Geog. Soc., Vol. 44, 1912, p. 354 *et seq.*

of the earth by gravity. The surface of the earth may, therefore, be considered as a mosaic of great polygonal blocks (Fig. 355), which from time to time suffer readjustment, the areas occupied by the continents being the continental segments and those by the oceans being the oceanic segments. Not only is the earth divided into these great segments, but these in turn are made up of smaller blocks which by differential movements have produced the high plateaus and low plains of the continents, and the "deeps" of the oceans.

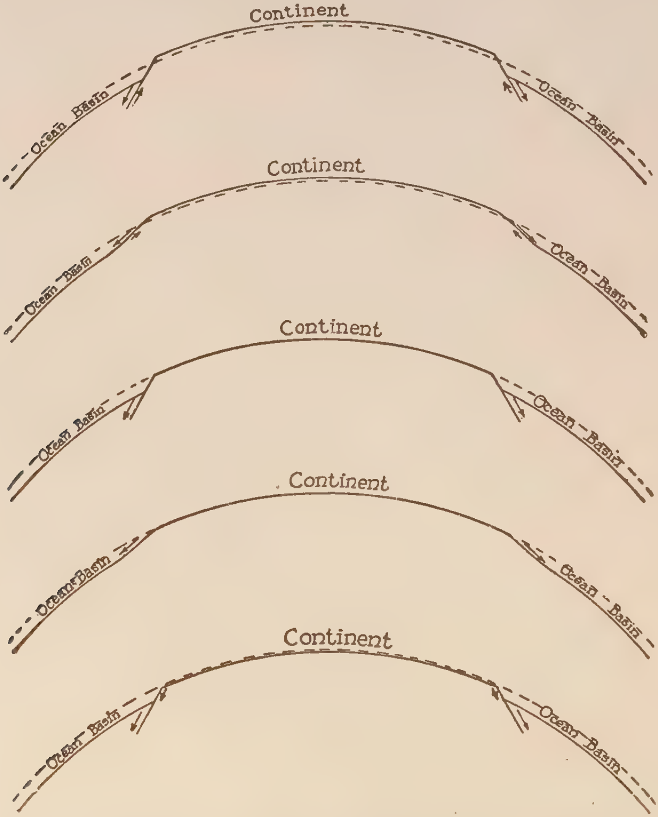


FIG. 355. — Diagrams representing the conception that the continents were lifted and the ocean basins sunk by movement along definite sliding planes or *fault planes*. The dotted lines may be taken to represent a somewhat uniform original surface, which may be looked upon as the surface before the continents and ocean basins were developed. (After Salisbury.)

The theory of isostasy holds that every segment of the earth, having an equal area of surface and with its apex at the center, contains the same amount of material, which it is impossible materially to increase or decrease. When a large quantity of material is removed from the land by erosion and deposited in the ocean by streams, the increased weight under the ocean and the decrease under the mountains will cause the rock at a great depth to flow from the area which is more heavily weighted, to that from which the weight has been removed, and the approximate equality of material in the segments will thus be restored.

As the oceanic and continental segments are drawn toward the center of the earth, the surface portions are subjected to great lateral pressure produced by the crowding of the segments against one another, and since the pressure cannot be relieved by the transfer of material by rock flowage such as is possible at great depths, it is relieved by folding and thrust faulting. Since, as has already been shown, the materials of the great mountain ranges were formed from the thick sediments of geosynclines whose basal portions were probably weakened to some extent by the invasion of heat from the interior of the earth, it is clear that, if such thick but weak strata are subjected to great horizontal compression, they will be likely to be folded and faulted. According to the theory of isostasy, however, the folding of strata by lateral pressure could not cause the elevation of a mountain range *without the aid of the expansion of the material* of which it is composed, since otherwise the *quantity* of material in the segment would be increased by folding and this added weight would cause a slow sinking, and material would flow from below the heavier segment to the lighter one, until the two again balanced.

This theory does not tell us definitely the cause of the elevation of mountains and plateaus, but it positively states that the elevation of mountains or the depression of oceanic segments must be due to an increase or decrease of density. The mountains are high because their material is light, and their elevation is due to an expansion of the material in and under them; the ocean deeps are depressed because the material under them is dense and may be sinking because this material is becoming denser.

A number of examples of mountain ranges which owe their height to vertical elevation can be cited. The present altitude of the Appalachians, as has been stated, is the result of vertical movement without the aid of lateral pressure, the folding of the strata long yr 35-39 //

antedating the last elevation. The Sierra Nevadas, after folding, were peneplained and were later elevated along a great fault on the east, and their height is being increased at the present time. It is thus seen that the elevation of high mountains may be due to vertical movements, without the aid of folding.

The Distribution of Mountains. — Attention has long been called to the fact that the mountain ranges of the Pacific — the Andes, western ranges of North America, etc. — are situated near the edges of the continents, and the generalization has been made that mountains are usually located near the oceans, the higher mountains bordering the deepest basins. It is also to be noted that many exceptions exist: the Alps, Caucasus, Urals, and Himalayas are situated at considerable distances inland. The distribution of mountains has led to two theories as to the position of the geosynclines in which the sediments forming them were accumulated; one holding that the geosynclines existed at the *edges of the continents*, the other that they were *between land masses*. The apparent exceptions to the latter theory are attributed to the subsequent sinking of lands which formerly existed near the present shores of the oceans bordered by mountains. According to this theory, for example, the Alpine geosyncline existed between the African continent and the ancient land masses on the north; the Appalachian geosyncline, between the Piedmont land on the east and other ancient lands on the north and west (p. 477); the Himalayas, between the Indian peninsula and land to the north.

Permanence of Continents and Ocean Basins. — It is quite generally agreed by geologists that the ocean basins and the continental platforms have been very much as now for many millions of years. By this is meant that the present continents have not been covered by oceans thousands of feet deep, nor have the ocean depths been dry land over wide areas. The proof of the former lies in the fact that no deep-sea sediments have ever been found in the sedimentary rocks of the continents, the continents having been covered repeatedly by shallow seas (called epicontinental, p. 405), but never by any of great depth. Of the latter no positive proof has been advanced, but on the contrary the distribution of animals and plants in the past gives reason for believing that land connections once existed between South America and Africa, North America and Europe, and Australia and Africa.

Age of Mountains. — This subject will be more fully discussed later (p. 519), but it should be noted in this connection that the time at which a region was raised above the sea was, at least, not previous to the youngest rocks of which the region is composed. For example, the Appalachian Mountains contain coal beds which show that the region was folded after their formation, *i.e.*, after the Carboniferous (p. 477).

REFERENCES FOR MOUNTAINS

Bowie, W., — *The Earth's Crust and Isostasy:* Geographical Review, Oct. 1922, pp. 613–627.

Daly, R. A., — *Abyssal Igneous Injection as a Causal Condition and as an Effect of Mountain-building:* Am. Jour. Sci., Vol. 22, 1906, pp. 195–216.

Daly, R. A., — *Mechanics of Igneous Intrusion:* Am. Jour. Sci., Vol. 15, 1903, pp. 269–298; Vol. 16, 1903, pp. 107–126.

Daly, R. A., — *Igneous Rocks and their Origin.*

Geikie, J., — *Mountains; their Origin, Growth, and Decay.*

Geikie, A., — *Textbook of Geology*, 4th ed., Vol. 1, pp. 672–702.

Gilbert, G. K., — *Report on the Geology of the Henry Mountains:* U. S. Geol. and Geog. Surv. of the Rocky Mountain Region, 1877.

Willis, B., — *The Mechanics of Appalachian Structure:* Thirteenth Ann. Rept., U. S. Geol. Surv., Pt. 2, pp. 217–281.

TOPOGRAPHIC MAP SHEETS, U. S. GEOLOGICAL SURVEY, ILLUSTRATING MOUNTAINS OF VARIOUS ORIGINS

Folded Mountains

Delaware Water Gap, Pennsylvania.
Harrisburg, Pennsylvania.
Hollidaysburg, Pennsylvania.
Estillville, Kentucky.
Fort Payne, Alabama.
Tamalpais, California.

Residual Mountains

Kaaterskill, New York.
Mt. Mitchell, North Carolina.
Monadnock, New Hampshire.
Wausau, Wisconsin.

Fault Mountains

Alturas, California.
Granite Range, Nevada.

Laccolith Mountains

Henry Mts., Utah.

CHAPTER XII

ORE DEPOSITS

Ores are concentrations in the earth's crust of economically valuable minerals.

Ores in Ready-made Cavities. — A common form of deposit is the *vein*, or the filling of a fissure in a rock. The contents of a fissure may consist partly or wholly of minerals, some of which may or may not be of economic value. When mineral veins contain ores, they are called *lodes* by miners. Fissures and other cavities are formed in several ways, as has been seen (p. 262). (1) Stretching movements of the earth's crust fracture it, producing open cracks; (2) faulting (p. 261) forms fissures and brecciated zones; (3) fissures are developed by shrinkage, such as occurs when igneous rocks cool or when limestone is changed to dolomite; (4) the joints of rocks are widened; (5) cavities are formed in limestone by solution. Cavities formed in any of these ways may contain ores.

Fissure Deposits. — Metalliferous veins are not composed entirely of metalliferous minerals, but on the contrary the latter often constitute a very small percentage of the vein filling. The useless vein material is called *gangue*, the common gangue minerals being quartz, calcite, and fluorite. In some veins the contents are arranged in bands parallel to the walls, the minerals and ores of one wall being represented by corresponding bands on the opposite wall (Fig. 356). This arrangement is the result of the deposition of minerals from solution on the two walls of the fissure at the same time. Such a symmetrical arrangement, however, is not common, the layers usually being thicker on one wall than on the other, while frequently a layer on

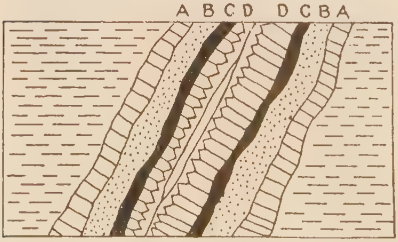


Fig. 356. — Banded veins: *A* and *D*, quartz; *B*, sphalerite; *C*, galena.

one side has no corresponding layer on the other. A banded structure may also be brought about when, as a result of movements which rend the vein from one of its walls, the fissure is reopened and minerals are subsequently deposited in the cavity thus formed. Several such movements may take place and two or more bands may be formed. In some veins the filling consists wholly or in part of broken rock (Fig. 357), the spaces between which are filled with quartz or other minerals.

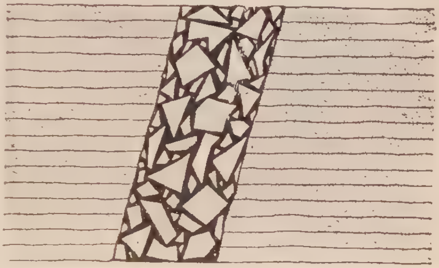


Fig. 357. — A section showing a fault breccia. Such breccias have sometimes been cemented together by precious minerals and are valuable ore deposits. (After Ries and Watson.)

Form and Extent of Veins. — The form of veins usually depends upon the shape of the fissures which they fill, and their width, length, and depth consequently vary greatly. Some are only a fraction of an inch wide, while others are 200 or 300 feet in width. The length is even more variable, being in some cases 50 or more miles and in others only a few feet. Some veins have been followed to a depth of more than 5000 feet, while others have disappeared a few feet beneath the surface.

Source of Vein Material. — It has been shown by chemical analysis that nickel, copper, tin, lead, and other metals occur in minute quantities in both sedimentary and igneous rocks, and it is generally believed that the ores which are now concentrated in veins were originally disseminated through the rocks; that they have been dissolved out by water, carried to fissures or other cavities and there deposited. This theory is borne out by the fact that in certain places veins are actually being formed at the present time by deposition from water. For example, near Boulder, Montana, a hot spring is depositing gold-bearing quartz identical with the gold and silver-bearing quartz veins of the region. Steamboat Springs, in Nevada, are strongly alkaline and are depositing quartz in fissures and thus forming veins. Sulphides of iron, lead, mercury, and zinc are found in recently filled fissures.

The water which acts as a transporting agent is either *meteoric* (rain water) or *magmatic* (the waters issuing from cooling masses of rock). The latter are believed by many geologists to be the more effective carriers of metalliferous minerals in the majority of deposits, although meteoric waters were apparently the sole agents in some cases. Gases and vapors given off by molten magmas have also formed some deposits.

The importance of igneous intrusions in the production of ore deposits is readily understood when the history of such an intrusion is considered. When a sedimentary rock, for example, is penetrated by a molten mass, it is more or less fractured. In these fractures the waters heated by the igneous mass can circulate, and if they contain minerals in solution the latter may be precipitated. Moreover, igneous rocks are often rich in metallic minerals, and the water derived from them, the *magmatic waters*, may be the chief source of the metallic minerals of the ore deposit.

Cause of Precipitation. — Veins exist only in the *zone of fracture*, that is, at a depth seldom as great as 10 or 11 miles, and in most cases within a mile or two of the surface. The precipitation of minerals in veins may be brought about in one of a number of ways. (1) It may be caused by the mingling of waters. This is due to the fact that having pursued different courses the waters may carry different salts which may react to cause the precipitation of metallic and other minerals. (2) Precipitation may also be brought about by the contact of solutions with rocks which contain carbon or other minerals which cause precipitation; (3) by a decrease in temperature; (4) by a change in pressure; and (5) by oxidation (if the solutions are brought near the surface). (6) If two rocks differing in chemical composition are in contact, as, for example, a limestone and an igneous rock, precipitation is favored at or near the plane of contact, since the waters from the two are differently mineralized.

When a mineral has once formed on a fissure wall, it may act as a center of attraction and cause a further accretion of the same mineral. This process is called *mass action.*

Replacement Deposits. — Waters carrying minerals in solution sometimes attack the rocks which they penetrate, dissolving them and at the same time depositing some of their load. This is accomplished molecule by molecule, a particle of vein material being deposited as a particle of the rock is dissolved out. Many of the rich ore deposits are of this origin. Replacement deposits often occur along faults and near the boundary or *contact* of igneous with sedimentary rocks.

The boundaries of veins are often indefinite, since the width may depend either upon the width of the original fissure or upon the amount of the replacement of the walls, or upon both. If replacement has not occurred, the boundary of the vein may be distinct.

Weathering and Concentration of Ores. — As a metalliferous vein is eroded, it is attacked by the agents of the weather and underground water. The result of such action is the removal of the more soluble minerals in the *surface zone*. (1) If the minerals removed are worthless, the portion remaining will be richer. For example, in gold-bearing quartz veins in which the gold is contained in pyrite, the solution of the pyrite leaves the pure gold in a honeycombed, rusty quartz. It was such quartz veins which delighted the old-time prospector.

(2) If the minerals removed are valuable and are deposited lower in the vein by the percolating water, a rich deposit may result. In a vein containing chalcopyrite and pyrite, for example, the iron may be left in the upper part of the vein in in the form of limonite. This is called the *gossan* (*chapeau de fer* and *eisen hut*) and may be in sufficient quantity to be mined as iron ore (Fig. 358).

Fig. 358. — A vein showing four zones: (1) a weathered or leached zone, (2) an oxidized zone, (3) a rich sulphide zone formed by material carried down by percolating water, and (4) the unaltered vein material. The weathered zone may be composed largely of limonite. (After W. H. Emmons, *General Economic Geology*.)

Lower in the vein, in the *oxidized* or *middle zone*, the ores are in the form of oxides, carbonates, etc., and may be enriched by the addition of metallic minerals brought down from the weathered zone. In some deposits the oxidized zone is the only portion of the vein in which the mineral occurs in sufficient quantities to be extracted with profit.

Beneath the oxidized zone, which extends to or below the level of ground water, lies the unaltered vein material of the *unoxidized zone*. Here the ores occur as they were originally deposited. These three zones are not usually separated by well-defined boundaries, the change from one to the other being sometimes so gradual that it is difficult to say where one begins and the other ends. Veins are known in which oxidized ores occur several hundred feet below the water table.

Magmatic Segregation. — Certain iron and nickel deposits which occur in igneous rocks were probably brought together while the rocks were in a molten condition as the result of segregation. Few workable deposits, however, have been formed in this way.

Placer Gold Deposits. — In the early days of gold mining in many countries the first gold was found in the gravels of stream beds. The gold of the Klondike in northwestern Canada and the majority of the early finds of Alaska were located in stream gravels, while that of Nome was found in the sands of the seashore. The gold rush to California in 1849 was due to the finding of stream or *placer* gold. The source of the nuggets or dust in stream gravels is evidently to be found in the rocks over which the streams or their tributaries now flow or formerly flowed.

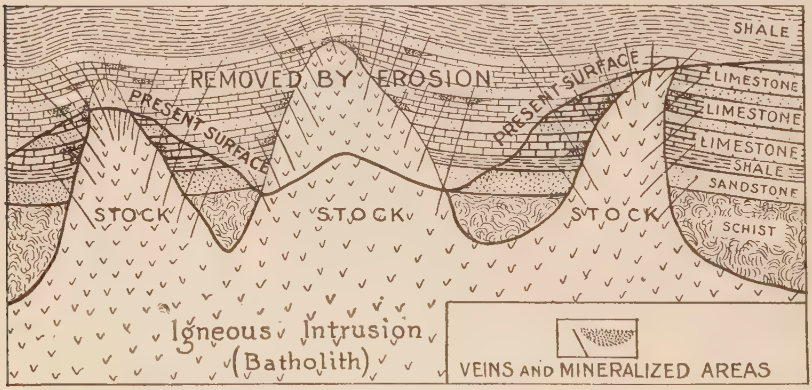


FIG. 359 *A*. — Diagram showing the occurrence of ore in veins and replacements. The loss of ore by erosion is well shown. The source of ore is the batholith. (Modified after Butler.)

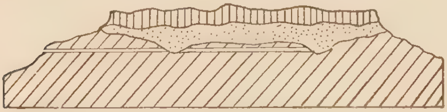


FIG. 359 *B*. — Diagram showing ancient auriferous gravels (dotted) covered by a lava flow (vertical lines). In mining the gravels a tunnel is driven as indicated.

The way in which placer gold was transported and deposited is simple. The gold occurred either in veins or scattered through the country rock in small quantities. When these rocks were disintegrated by weathering and the fragments carried away by the streams, the heavy gold particles quickly sank to the bed of the streams, while the lighter minerals were borne on by the current. In this way much of the gold contained in a large quantity of rock has sometimes been concentrated in a small area. It consequently happens occasionally that rich placer deposits are found in regions in which none of the rock contains gold in sufficient quantity to pay for its extraction.

When conditions are favorable, gold-bearing (auriferous) gravels are worked by dredging, even when the gravel yields only twenty-five or thirty cents to the cubic yard. Ancient gravels which have been buried beneath sheets of lava are sometimes mined for their gold (Fig. 359 *B*).

Sedimentary Iron Deposits. — Extending in a broken belt from Nova Scotia and New York to Alabama, beds of iron ore (Clinton iron ore) occur which have the same position and much the same character as other sedimentary beds, and in some cases contain marine fossils. These beds of iron ore may have been precipitated from salt or from fresh water, just as iron is being deposited to-day in fresh-water ponds and lakes. The iron contained in small quantities in the rocks (usually igneous) of the land is leached out by percolating waters in the form of ferrous compounds. These compounds upon exposure to the air are oxidized and ferric oxide (Fe_2O_3) is precipitated, usually in the form of limonite ($2\ Fe_2O_3 \cdot 3\ H_2O$). In this way iron accumulates in bogs and is called *bog ore*, and similar deposits are laid down in lakes. Another suggestion which, however, is not widely accepted, is that the Clinton iron ore has been derived from lavas rich in iron minerals which were extruded beneath the sea.

FIG. 360. — Iron deposits in the Lake Superior region, Mesabi Range, Minnesota. (U. S. Geol. Surv.)

The great iron deposits of the Lake Superior region (Fig. 360) are believed to have been accumulated in beds as impure iron carbonates and silicates, too low in iron to pay for their extraction. When the deposits were uplifted to form land, they were exposed to weathering and were enriched (1) by the removal of the impurities by solution; (2) by the *replacement* of the impurities by iron oxides as the former were dissolved out; or (3) by concentration, as a result partly of the removal of impurities and partly of replacement.

So wide and deep are some of these Lake Superior iron deposits that they are excavated by steam shovels. The excavation in the Mesabi region, taking into account both the removal of the ore and of the glacial drift which overlies it, is far more extensive than the work conducted at the Panama Canal. In most of the deposits underground mining methods are employed.

REFERENCES FOR ORE DEPOSITS

EMMONS, W. H., — *Principles of Economic Geology.*
LINDGREN, W., — *Mineral Deposits.*
RIES, H., — *Economic Geology.*
U. S. Geol. Survey Bulletins, Professional Papers, and Monographs.

PART II. HISTORICAL GEOLOGY

CHAPTER XIII

HISTORICAL GEOLOGY

HISTORICAL geology deals with the evolution of the life of the past, and with the development of the continents and oceans. It traces out, as accurately as our present knowledge will permit, the changes through which the earth has passed; it endeavors to gather from the available record the history of the life of geological times and the evolutional changes which the many classes of animals and plants have undergone and, as far as possible, to determine the cause or causes of these changes. This section of geology is concerned not only with the recording of facts, but is also, to an important degree, philosophical.

Human history is but a short chapter of geological history, the former being measured in thousands of years while the latter extends over millions of years. The immensity of geological time is beyond our comprehension, but some conception of it can be gained when it is remembered that the time necessary to excavate the Grand Canyon of the Colorado was, geologically, comparatively short; that a maximum thickness of sediments of not less than 40 miles has been laid down in the seas; that great mountain ranges have not only been raised but have been worn down to sea level during portions of the smaller divisions of geological history. Perhaps the most striking evidence of the length of geological time is to be seen in the evolution of life.

FOSSILS

A fossil is any remains or trace of an animal or plant preserved in the rocks of the earth. It may consist of the original substance of the animal, or it may be merely an impression, such as a footprint or a worm trail. Even the flint implements made by primitive man may be considered as fossils.

When a shell or other organic remain is buried in the mud or sand of an ocean or lake bottom, in the dune sand of a desert, in volcanic dust, in a peat bog, or in the flood plain of a river, the record of its existence may be preserved in a number of ways.

(1) *The Original Substance may be Preserved.* — In recent sediments the shells are often unchanged, even the nacreous luster being retained. In the ice of Siberia mammoths have been found whose flesh had been so perfectly preserved that it was eaten by dogs and wolves and possibly by the natives themselves. Insects are found in amber — the fossil gum of cone-bearing trees — in which they were entrapped and covered.

(2) *Replacement.* — The original substance may have been entirely replaced by some other mineral, and shells, corals, and bones are often found which, although bearing little external evidence of alteration, are composed entirely of silica or some other mineral.

As alkaline water is a solvent of silica the petrifaction of wood (Fig. 361) is brought about when such water containing silica in solution is neutralized, since the silica is then precipitated. If then a log buried in a bed of sand or volcanic ash is saturated with underground water that is slightly alkaline, the replacement of the wood by the silica will be slowly brought about as the wood decays. As each particle of wood is oxidized carbon dioxide will be formed, this acid (H_2CO_3) will neutralize the alkali of the water and will cause the precipitation of the silica at the point where the wood decayed. By some such slow process the wood may be replaced particle by particle until the entire tree is converted into a solid cylinder of silica.

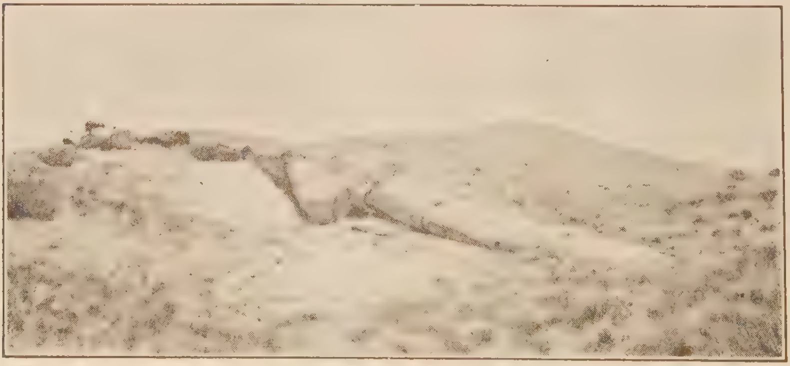


FIG. 361. — Petrified log, Adamana, Arizona.

Silica is not the only mineral which replaces the substance of shells, bones, and other hard parts. Pyrite, iron oxide, lime carbonate, and other minerals sometimes occur.

(3) *Casts and Molds.* — The original substance may be carried away in solution by underground water, leaving a cavity in which only the external form is preserved; in other words, a *mold* of the shell or bone is left. Often natural *casts* of these molds are formed by mineral matter carried into the mold or by the infiltration of mud. Molds of the interior (Fig. 362) and exterior (Fig. 363) are frequently encountered in porous rocks. Some fine opals in Nevada have the form of branches, but are in reality casts of the branches of trees, the cavities formed by the decay of the wood having been filled with silica.

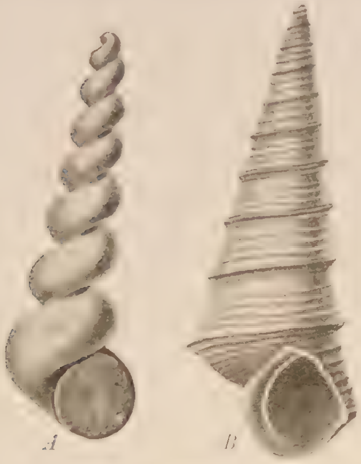


FIG. 362. — Specimens showing the original shell (*B*) and a natural mold (*A*) of the interior of a similar specimen from which the shell has disappeared. (*Turritella mortoni.*)

FIG. 363. — One half of a concretion showing the leaf which formed the nucleus.

(4) *Footprints, Trails, etc.* — Many animals are known from their footprints, trails, burrows, or the impressions (Fig. 380, p. 411) made by their bodies in the soft mud.

Entombment of Plants and Animals. — The most favorable conditions for the preservation of animal life are to be found on those portions of the ocean bottom which are not uncovered by tides and where sediments are accumulating. When under such conditions shellfish or other animals die, their bodies may be buried in the mud or sand and preserved. It is not unusual to find layers of rock made up largely of the remains of shells which were buried in this way. On the surface of some slabs of rock 250 or 300 fossils may sometimes be counted.

Animal and plant remains are often well preserved in lake deposits. In deposits of this class are found leaves, branches, and flowers which were carried from the surrounding land by the streams, insects which were beaten down by the wind to the surface of the lake, and vertebrates which were floated down the streams and found a burial on the lake bottom. Some of the most beautiful fossils were made in this way, but deposits of this class are much less important than those of marine origin, both because of their smaller extent and because the contained fossils seldom afford a means of exact correlation with those of other countries.

The fossils preserved in delta swamps and flood plains are often numerous, and during certain periods of the earth's history have afforded the chief record of the vertebrates of these periods.

Fossils are also preserved in wind-blown sand, in peat bogs, in caverns, and in travertine.

Imperfection of the Record. — The record of ancient life must necessarily be imperfect for two reasons. (1) Only a small percentage of the life of any one period is preserved. This can be seen best by observing the proportion of the plant and animal life of to-day that will remain as a record of the life of the twentieth century. Of the life of the sea only the animals with shells or skeletons will be preserved in large numbers; the myriads of soft-bodied animals such as jellyfish and protozoans will not form recognizable fossils except under very exceptional conditions. The trees of the forest decay where they fall, and it is seldom that any are buried and leave a permanent record. The same fate awaits land animals, since upon their death their bones are soon disintegrated by the agents of the atmosphere and they crumble to dust. It is only the bones of the occasional carcass which floats downstream and is buried under favorable conditions that will form fossils.

(2) Even after being buried, the record is not always preserved. Thousands of square miles of sediments have been metamorphosed and the contained fossils destroyed. When marine sediments have been raised to form land, they are immediately attacked by the weather and erosion and are soon carried away. We consequently find that thousands of feet of rock have been removed and the record has been completely lost. Much of the fossiliferous strata is also either buried so far beneath younger rocks as to be inaccessible

or is under the waters of the seas and so beyond the reach of the geologist.

Geological Chronology

Relative ages of strata are determined in two ways.

(1) *Order of Superposition.* — If a series of strata or beds is in the order in which they were laid down (Fig. 364), it is evident that the oldest will be at the bottom and the youngest at the top. It is for this reason that the strata of a geological section are always placed with the oldest at the bottom of the column. This order is conclusive proof of the relative age of rocks unless they have lost their original position by faulting or folding.

(2) *Chronology Determined by Fossils.* — After the true order of a series of beds has been determined by their superposition, their contained fossils will usually make it possible to correlate them with strata which may be hundreds or even thousands of miles distant. This is rendered possible by the fact that the inhabitants of the earth have undergone a progressive change which has, as a whole, been gradual, but which has taken place more rapidly at certain times than at others. Certain classes became dominant for a time, and then declined but seldom entirely disappeared. As a result of this change the assemblage of animals and plants of each division of geological history differs from that of every other. The fact that life has suffered such a progressive modification is of the greatest importance, since, as already indicated, it furnishes a means by which the relative age of the rocks in different parts of the world can be determined. Since certain species have a short geological life (their *vertical range* is short), when such are present the relative age of the rock is readily fixed.

Although fossils are the surest test of the relative age of widely separated strata it should not be concluded that they prove exact contemporaneity, since in favored regions an old fauna may live thousands

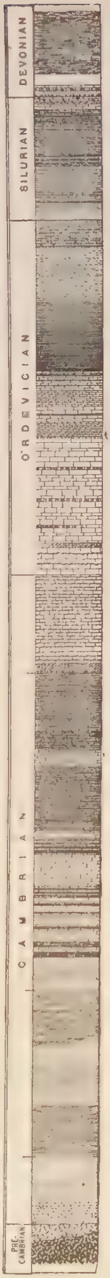


Fig. 364. — A composite section in Pennsylvania, showing strata from the Pre-Cambrian through the Devonian. The vertical thickness represents about 21,000 feet.

of years after it has become extinct in others. An example is found in Australia to-day, where the indigenous fauna belongs to the early Tertiary.

Use of Fossils in Determining Physical Conditions. — A study of the inclosed fossils usually tells definitely whether the rocks were laid down in the sea, in a lake, or on land. Fossils also give a clue to the depth of the water and the proximity of the shore. Corals show that the deposits containing them were laid down in warm seas some distance from land, or that the land was so low that little sediment was carried to the sea. Leaves and stems of plants as well as the fossils of land animals indicate nearness to shore.

The climate of the past is also told with considerable certainty by fossils. For example, relatively recent travertine deposits of northern France contain the canary laurel, a plant which blooms in winter and which now grows in the moist climate of the Canary Islands, where the temperature seldom falls below 59° F. It is evident, therefore, that when the canary laurel grew in northern France the climate of that region was probably warm and moist. The occurrence in the Pleistocene deposits of Denmark and England of Arctic willows which now grow only within the Arctic Circle is evidence of a cool climate in the past in those countries.

A typical example of the knowledge to be gained of the physical geography and climate of a region by a study of the fossils is illustrated by the limestones of Wisconsin. These strata are composed of practically pure limestone, being free from land sediments, and contain fossil corals, crinoids, brachiopods, and the remains of other marine animals. It is evident, therefore, that when the limestone was accumulating, a sea spread over a portion at least of Wisconsin, that the region in which the lime ooze was deposited was probably far from land, and that the climate, as shown by the corals, was probably warm.

Difficulties in Correlating Strata. — (1) When rocks have been overturned or faulted, older beds are sometimes found to rest on younger ones. (2) In some regions a once widespread stratum may be represented now only by isolated patches which may be separated by distances of several miles. (3) Strata are sometimes separated by an unconformity (p. 270) which may represent a lost interval of many years. (4) The lithological character of a stratum may vary greatly even over short distances. In every case, however, fossils if present will usually give definite knowledge of the relative age of the rocks.

Since in no one region are the strata of even a majority of the systems of the earth represented, it is evident that one of the difficulties of geology is to bring together the data and place them in their true order so as to make a complete and accurate record. For example, unconformities representing a loss of two or three systems may occur in two sections, but when the two sections are compared it may be found that they complement each other, that which is lacking in the one being present in the other and *vice versa.* It is evident that when such sections exist, a complete record of a portion of geological time is available.

The difficulties may be seen by a study of the rocks upon which the city of Paris is situated. An examination of these strata shows that, at least ten times in the past, this region was covered by the sea and sediments accumulated on the sea floor, and as many times the sea bottom was raised above the water and was subjected to erosion. When the latter occurred, no sediments preserve the fossils of the periods during which land existed, and it is only by studying the fossils in strata of other regions that the whole history can be read and the age of the strata which are present be determined.

DIVISIONS OF GEOLOGICAL TIME

The broad outlines of the earth's history have been learned as a result of such studies as those indicated above, and have been arranged in chronological order and separated into more or less clearly marked divisions which correspond to the chapters of human history. The divisions of time and corresponding divisions of the rocks have been given the following terms:

TIME SCALE	ROCK SCALE
Era	Group
Period	System
Epoch	Series
Age	Stage

An *era* consists of several *periods* during which a *group* composed of several *systems* of strata were accumulated. During an *epoch* a *series* composed of one or more *stages* was laid down. When one speaks of the *Cambrian System*, he means the succession of strata which were laid down in the *Cambrian Period;* when he speaks of the *Miocene Series*, he refers to strata deposited during the *Miocene Epoch*, *i.e.*, during a definite portion of the *Tertiary Period.*

The following table includes the more important divisions of the geological record:

Cenozoic	Era and Group	Quaternary	Period and System	Recent	Epochs and Series
				Pleistocene	
		Tertiary	Period and System	Pliocene	Epochs and Series
				Miocene	
				Oligocene	
				Eocene	
Mesozoic	Era and Group	Cretaceous	Period and System		
		Jurassic	Period and System		
		Triassic	Period and System		
Paleozoic	Era and Group	Carboniferous	Period and System		
				Permian	
				Pennsylvanian	
				Mississippian	
		Devonian	Period and System		
		Silurian	Period and System		
		Ordovician	Period and System		
		Cambrian	Period and System		
Pre-Cambrian Eras		Proterozoic Era and Group			
		Archæozoic Era and Group			

REFERENCES

Grabau, A. W., — *Principles of Stratigraphy*, pp. 1073–1095.
Schuchert, Chas., — *Text Book of Geology*, Pt. II, Historical Geology.
Scott, W. B., — *An Introduction to Geology*, pp. 516–531.
Shimer, H. W., — *An Introduction to the Study of Fossils*, pp. 8–28.

CHAPTER XIV

THE EARTH BEFORE THE CAMBRIAN

SPECULATIONS and theories as to the origin of the earth are as old as the human race, but of the many that have been offered only two are based upon physical laws, and these only demand our attention.

THEORIES OF THE EARTH'S ORIGIN

Nebular Hypothesis. — The theory of a molten earth is generally associated with the Laplacian or nebular hypothesis of the earth's origin, although in a modified form the hypothesis holds that the earth has never been in a molten condition. This hypothesis, in brief, holds that the material of which the sun, earth, and other planets are composed was once in the form of a vapor (nebula) diffused throughout the space now occupied by the solar system and extending some distance beyond the orbit of the outermost planet (Neptune). This great mass of vapor began to rotate because of contraction and formed a much-flattened spheroid. As contraction continued, a time came when the centrifugal force of the particles near the equator of the mass was equal to the pulling force of gravity, and they were left as a ring, while the remainder of the mass continued to contract. This process being repeated successive rings were abandoned. Each of the rings thus formed probably revolved for a time as a whole, but finally broke up, the material of each ring being concentrated into a single planet with its satellites, the satellites being formed from rings abandoned by the planets as they contracted, just as the planets were formed from the parent nebula. In this way, according to the nebular hypothesis, the planets were originated, the sun remaining as the central and uncooled portion of the nebula.

According to this hypothesis, therefore, the earth was first a globe of highly heated vapor which was later condensed to a liquid and was finally cooled sufficiently to permit of the formation of a crust over the surface, while the interior was still a liquid. In this early stage the atmosphere was very heavy and hot, and contained not only all the water now on the earth, but many of the gases that are now united with other elements to form the rocks. When the crust finally cooled to such an extent that water could remain on its surface, the oceans were formed and the atmosphere gradually lost its gases until its present composition and character were attained.

Planetesimal Hypothesis. — The planetesimal hypothesis has been offered as a substitute for the nebular hypothesis. Omitting the astronomical considerations, this theory assumes that the earth was never in a molten condition, but grew gradually by the ingathering of small particles (Fig. 365) called *planetesimals* (little planets).

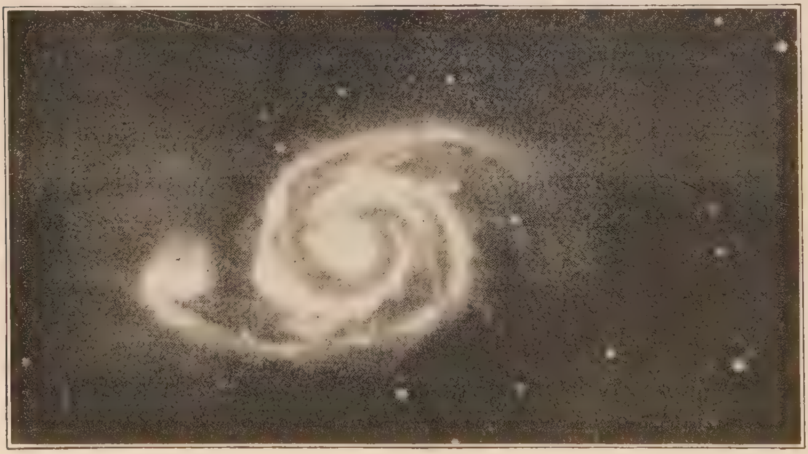


Fig. 365. — Spiral nebula. (Yerkes Observatory.)

In its early stages, if this hypothesis is true, the earth had no atmosphere, since, on account of its small mass, the attraction of gravity was insufficient to hold the gases which were lost in space because of their activity. With its present mass the earth's attraction is sufficient to prevent the escape of most of the gases, but such gases as hydrogen and helion are still superior to its attraction. The moon appears to be devoid of an atmosphere, the gravity of its mass being insufficient to hold the gases to it. When the earth was as small as the moon is now, it, too, probably had no atmosphere, but as it grew by the addition of meteoric matter, gravitational attraction increased, permitting it to bind to itself more and more gases until the present condition was reached. The gases first held by the attraction of the earth were the heavier ones, such as carbon dioxide, nitrogen, and water vapor. Of these, carbon dioxide, being chemically active probably entered into combination with the rocks to an important degree, while nitrogen, an inactive gas, has accumulated until it now constitutes about 79 per cent. of the atmosphere. The percentage of carbon dioxide in the atmosphere is about .03 of one per cent.

The atmosphere as now composed has been derived either directly from space, as when gases came within the influence of the earth's attraction and were held by it, or from the interior of the earth from which they were forced by the increasing heat produced by compression as well as by the pressure itself. When the water vapor condensed to form rain, streams began to cut down the land, underground waters began their work of solution and deposition, the depressions of the land were filled with water, and the earth's surface as we now know it began its long series of transformations.

Nebular and Planetesimal Theories Contrasted. — The nebular and planetesimal theories differ in a number of fundamental features. Under the former, the earth was once hotter and larger than now and by cooling and contraction has become smaller and solid, or nearly so. Under the planetesimal hypothesis, the earth became continually larger as its bulk was increased by the gathering in of planetesimals. The atmosphere of the earth, according to the theory of a molten globe, was heaviest at first; according to the planetesimal theory, it was lightest at the beginning and grew denser as the earth increased in size and mass. According to the one (nebular), we may hope to find the original igneous crust of the earth; according to the other (planetesimal), a "crust" never existed, but after the appearance of an atmosphere the surface was composed of lava flows, volcanic ash, meteoric matter, and sedimentary deposits.

The advocates of each of these theories agree that at present the earth is essentially a solid mass more rigid than steel or glass. This is shown by several lines of evidence: earthquake shocks (p. 283) pass directly through the earth and travel at a rate which shows that the transmitting medium is an extremely rigid substance; experiments have shown that enormous rigidity is imparted to such substances as molten rock by application of moderate pressures and, hence, even if the interior is molten it would be more rigid than steel.

REFERENCES FOR THEORIES OF THE ORIGIN OF THE EARTH

Chamberlin and Salisbury, — *Geology*, Vol. 2, 1906, pp. 1–132.
Croll, James, — *Climate and Cosmology.*
Moulton, F. R., — *An Introduction to Astronomy.*
Young, C. A., — *A Textbook of General Astronomy.*

PRE-CAMBRIAN ERAS

In no connection is the saying, "All beginnings are difficult," more true than in the study of the earliest chapters of the earth's history. This is the case not only because the rocks which preserve the record in a given region have been subjected to all the foldings and metamorphisms which have affected all the subsequent rock formations of that region as well as earlier ones, but also because no fossils have been found except near the close of the Pre-Cambrian, and these are few and fragmentary.

A brief classification of the Pre-Cambrian[1] of the Lake Superior region of North America is as follows:

Proterozoic (Greek, *proteros*, early, and *zoe*, life)			One or more series separated by unconformities to which local names have been given since it has not been possible to determine their equivalents in distant regions.
	Upper Proterozoic (Keweenawan) Unconformity Middle Proterozoic (Upper Huronian) Unconformity		Proterozoic in the Lake Superior region.
	Lower Proterozoic	Middle Huronian Unconformity Lower Huronian	
	Great Unconformity		
Archæozoic (Greek, *arche*, beginning, and *zoe*, life)	(Laurentian)		Mainly light-colored (acid) granites, gneisses, and schists. These are largely intrusive, but some may represent the surface upon which the Keewatin was laid down.
	(Keewatin)		Mainly dark-colored (basic) metamorphic rocks, composed largely of metamorphic lava flows and tuffs, with small amounts of metamorphic sediments.

---

[1] The United States Geological Survey includes all of the Pre-Cambrian rocks under the term Proterozoic and uses Archæan for the Lower (Archæozoic) and Algonkian for the Upper Proterozoic.

F. D. Adams considers that the Pre-Cambrian rocks have a threefold division which he designates as Eo-Proterozoic (Archæozoic), Meso-Proterozoic (Middle and Upper Huronian), and Neo-Proterozoic (Keweenawan), Proterozoic being used independent of any consideration of the presence or absence of life.

The Archæozoic Era

Distribution of the Archæozoic Rocks. — The rocks constituting the Archæozoic system are the oldest of which we at present have any knowledge and, as far as known, underlie all the younger rocks of the earth's crust. In regions which have been repeatedly uplifted and eroded the Archæozoic rocks are uncovered, and it is in such places that they have been studied. In North America the greatest area of Archæozoic rocks lies in the eastern half of Canada, where they have an area of about 2,000,000 square miles, forming an irregular mass around Hudson Bay and extending south into Wisconsin and Minnesota. This is often designated as the "Laurentian shield." In the Adirondacks of New York, in New England, and in a belt stretching from Maryland south into Alabama (Piedmont Plateau) are crystalline rocks which are partly of Archæozoic age. In the cores of the mountains of the western half of the continent and in other isolated patches they also appear at the surface.

Our detailed knowledge of the Pre-Cambrian of North America is largely confined to the region about the Great Lakes and the St. Lawrence River. Here excellent and fresh exposures have been developed by glacial erosion, and the presence of valuable deposits of copper, iron, nickel, cobalt, and silver has led to a careful study of the region.

Archæozoic rocks apparently corresponding to the Archæozoic of North America occur in Scandinavia and other parts of Europe, over a large area in Brazil, in central Africa, in China, in India, and elsewhere, but the determination of the age of the crystalline rocks of many regions is yet in doubt. It has been roughly estimated that the Pre-Cambrian rocks appear at the surface over one fifth of the land area. The term "surface" is used to mean that the formation is not covered by younger rock formations, although it may be hidden in many places by soil or glacial deposits.

The difficulty of any attempt to correlate the Archæozoic rocks of distant or isolated regions is obvious, since fossils are absent, and this exact method of determining the age of rocks is consequently unavailable. Moreover the fact that the lithological character of the rocks of a formation may vary greatly, even in short distances, makes such characters of a formation an extremely uncertain criterion upon which to base a correlation. However, since fossils are lacking, the lithological character, superposition, and the degree of metamorphism and deformation must be taken advantage of in making provisional correlations.

Characteristics of Archæozoic Rocks. — No rocks are more complex than those of this system. In fact, their very complexity is a character which aids in their determination. In the Lake Superior region (Fig. 366) the system is, in general, composed of a great series (Keewatin) made up predominantly of dark-colored (basic) schists and great masses of granitoid gneisses and light-colored (acid) schists (Laurentian) which have apparently for the most part been intruded into the Keewatin schists. The Keewatin schists are, therefore, as far as present investigation shows, the oldest rocks of the earth's crust (unless some of the gneisses prove to be of even greater age). They are composed largely of lava flows and tuffs, with occasional conglomerates, shales, and beds of iron ore, which have been folded, contorted, and so metamorphosed that their former condition is with difficulty recognized. They have, moreover, been broken by faults and by massive intrusions. Dikes through which was forced the lava that flowed over surfaces that have since been worn away now cut both the schists and the Laurentian granites and gneisses. Great batholiths (p. 328) of granite (Laurentian) occur so frequently as to make them almost characteristic of the Archæozoic systems, and in certain regions they constitute the larger part of the surface rock. These batholiths have, in turn, been broken, faulted, and intruded by lavas of later age, and these by even younger intrusions. Formerly, before they were recognized as intrusive masses, the granites and gneisses of the Archæozoic systems were considered to be portions of the original crust of the earth. That surfaces must have existed upon which the lava flows and ash deposits spread and from which the material was derived to form the sedimentary beds is obvious. Nevertheless, no such surface has yet been recognized with certainty, either because it is still buried beneath the overlying

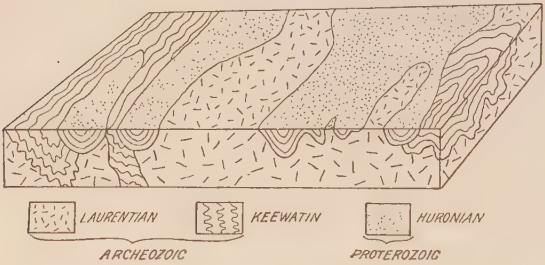


FIG. 366. — Block diagram showing the occurrence and complicated structure of Pre-Cambrian rocks in the Lake Superior region.

rocks or because it has been so welded into them by heat and pressure that it cannot be determined.

Thickness. — The rocks referred to the Archæozoic systems are of great but unknown thickness. The lower limits of the system, as stated, have never been observed, even where they have been cut down many hundreds of feet in mountain ranges or in the great "Pre-Cambrian shield" of Canada, which has apparently been repeatedly subjected to prolonged and profound erosion such perhaps as few other regions of the world have experienced.

Causes of Metamorphism and Deformation. — The cause of the metamorphic character of the Archæozoic rocks is readily understood when the disturbances which have affected them are considered. The Archæozoic was a time (1) of unusual igneous activity, as well as (2) of great deformations. Moreover (3) the rock that now appears at the surface was probably, for the most part, deeply buried beneath younger formations. These three factors alone would produce metamorphic changes of the first order. Deformation was produced in a number of ways (1) The great masses of magmas which were intruded into the rocks caused them to fold and crumple. Moreover (2) as molten rock was withdrawn from below the surface and poured out upon it, settling resulted which caused a further folding. These elements, taken in connection with (3) the lateral pressure resulting from the contraction of the interior of the earth (p. 359), must have altered profoundly the original structure and composition of the rocks, changing the lavas and tuffs and sedimentary rocks to schists of various kinds, and the granites to gneisses and even schists.

Conditions during the Archæozoic Era. — A few deductions can be made concerning the conditions which prevailed in this earliest era. The presence of successive lava flows and of volcanic ash and cinders shows that volcanoes were abundant and active, at least locally. The conglomerates and shales prove that the surfaces of the land were worn down by running water and that the rocks were weathered, since the clays of which shales are formed were produced by the weathering of igneous or other rocks. The presence of limestone suggests the possibility that shell-bearing animals were in existence, but since limestone is known to be formed by chemical precipitation as well as by organic remains, the evidence is not conclusive. The Grenville series of the St. Lawrence valley, estimated to be 50,000 feet thick, is distinctly stratified and is one of the greatest limestone series in the earth's crust, a part if not all of which is believed to be of Archæozoic age. Graphite, which may be metamorphosed organic matter, indicates the presence of plants. Graphite, however, may be of inorganic origin, derived perhaps from petroleum. No remains that can be positively identified as fossils have been found in the Archæozoic rocks.

It has been suggested (Daly) that the Pre-Cambrian limestones were entirely products of chemical precipitation. This is based on the assumption that the land areas were at first relatively small, and that the abundance of decaying, soft-bodied organisms on the sea floor produced ammonium carbonate, which led to a continuous precipitation of such lime as was available. Hence the ocean was limeless, and it was not until the lands became more extended that a sufficient quantity of lime salts was brought in by rivers to counterbalance that thrown down by the ammonium carbonate and sodium carbonate on the sea floor. If this be true, the earlier organisms could not form calcareous shells or skeletons. The fact that Pre-Cambrian and Cambrian limestones, even when unaltered, show no signs of having originated from shell remains is offered in proof.

Duration. — An immense but unknown duration is assigned to the Archæozoic era, an era so vast that even if it were possible to state the duration in terms of years the number would be so large as to convey little meaning to the human mind. If millions of years were consumed by the later eras, tens of millions must be ascribed to this era. In fact, it is possible that the Archæozoic may have been longer than all the subsequent eras taken together.

Bearing upon the Theories of the Earth's Origin. — (1) According to the theory that the earth was originally a molten globe (nebular hypothesis) which upon cooling first formed a crust, we should expect to find the earliest sedimentary rocks underlain by an igneous or metamorphic-igneous floor, provided that igneous activity was slight after the crust became cool enough to permit the operation of the agencies of erosion and the weather. It seems more probable, however, that in these early stages igneous activity would be unusually prevalent, with the result that lava flows, volcanic products of enormous thickness, as well as great intrusions might completely hide the original crust, if indeed it were not remelted.

(2) According to the planetesimal theory, the matter gathered in from space became so hot at the (*a*) center that it now forms an essentially igneous core. (*b*) A thick zone outside of the central core, made up largely of planetesimal matter, partly of igneous rock erupted from below, theoretically underlies the (*c*) next, and relatively thin zone which is composed largely of extrusive igneous rock, with smaller amounts of sediments and of planetesimal matter gathered from space. This is the zone which, according to the planetesimal theory, appears at the surface and is known as the Archæozoic.

It will be seen from the above that according to either the planetesimal or the modified nebular hypothesis the "crust" of the earth would have practically the same characters and that, therefore, even though fundamentally different, no means is afforded of testing the two theories.

I-ovr

Make less [illegible]

[illegible]

THE PROTEROZOIC ERA

Archæozoic and Proterozoic Contrasted. — The Archæozoic systems are separated from the overlying Proterozoic by a great and widespread unconformity (p. 270) upon which rests a series of rocks of enormous thickness, which extend to the fossiliferous Cambrian. The two groups differ in a number of particulars. "The Archæan [Archæozoic] is a group dominantly composed of igneous rocks, largely volcanic, and for extensive areas submarine. Sediments are subordinate. The Algonkian [Proterozoic] is a series of rocks which is mainly sedimentary. Volcanic rocks are subordinate. The Algonkian [Proterozoic] sediments, where not too greatly metamorphosed, are similar in all essential respects to those which occur in the Paleozoic and later periods. When the Algonkian [Proterozoic] rocks were laid down essentially the present conditions prevailed on earth. The Archæan [Archæozoic] rocks, on the other hand, indicate that during this era the dominant agencies were igneous. On the whole, the deformation and metamorphism of the Archæan [Archæozoic] are much farther advanced than the Algonkian [Proterozoic]. The two groups are commonly separated by an unconformity which at many localities is of a kind indicating that the physical break was of the first order of importance." (Van Hise.)

The Proterozoic in Different Regions. — *Lake Superior Region.* (Table, p. 388) South of the "Pre-Cambrian shield" (Fig. 367) the lowest member of the great series which constitutes the Proterozoic, is the Lower Proterozoic (Huronian, named from the fine development north of Lake Huron), and is composed of quartzites, slate, schists, interbedded lava flows, and igneous intrusions, together with limestone and beds of iron ore. The rocks are usually much folded and occur in the form of long, narrow belts, separated by the Archæozoic schists and gneisses, being small remnants of a once extensive system. Locally, at least, the Lower Proterozoic (Huronian) is

FIG. 367. — Section through a portion of northern Minnesota, showing the relation of the Pre-Cambrian rocks. (U. S. Geol. Surv.)

Proterozoic	*Akm*	Keweenawan.
	Ahl m	Huronian.
Archæozoic	Æ*l*	Granites and gneisses of the Laurentian.
	Æ*k*	Schists and iron-bearing formations of the Keewatin.

divided into two systems (Lower and Middle) by an unconformity.

Resting unconformably upon the Lower Proterozoic (Middle Huronian) is the Middle Proterozoic (Upper Huronian), which resembles the lower system lithologically in that it is composed of similar sedimentary rocks and lava flows, but is somewhat less metamorphic. In this system occur the largest and richest deposits of iron in North America. The unconformity which separates the Lower Proterozoic (Lower and Middle Huronian), and Middle Proterozoic (Upper Huronian), is considered by some geologists to be of an importance almost equal to that between the Archæozoic and Proterozoic systems.

The closing system of the Proterozoic (Keweenawan), separated from the Middle Proterozoic (Upper Huronian) by an unconformity, differs from the preceding Proterozoic systems in the presence of numerous, and in the aggregate enormously thick lava beds, which apparently welled up through fissures (much as in Iceland to-day) and did not flow from distinct volcanoes. The total thickness of these lava flows is estimated at nearly six miles, making this the most notable time of local volcanism in geological history. In northwestern Minnesota and contiguous portions of Wisconsin there are sixty-five distinct lava flows and five conglomerate beds, none of the former being more than 100 feet thick. In the section cited neither the upper nor the lower limits are known. The maximum thickness of the Keweenawan is estimated at 50,000 feet, of which sedimentary beds constitute about 15,000 feet. Towards the close of the period the igneous outbursts became less frequent, with a corresponding increase in the proportion of sedimentary deposits. The great Lake Superior copper deposits which have up to this time yielded many millions of dollars in profits to their owners occur in the lavas and conglomerates of this system. (The Keweenawan is by some writers considered to be Cambrian.)

The unconformities which separate the various systems of the Proterozoic in the Lake Superior region are well marked. They are evidenced (1) by basal conglomerates (p. 240) that represent the shores of an encroaching sea, (2) by the irregular erosion surfaces of the underlying rocks, (3) by differences in the amount of volcanism, and (4) by the differences in the metamorphism of the sediments of the overlying and underlying formations.

In the Grand Canyon of the Colorado the Pre-Cambrian formations (Fig. 368) are more than 10,000 feet thick and differ in many

FIG. 368. — Photograph of the wall of the Grand Canyon of the Colorado River, Arizona, showing two unconformities. (See Fig. 369.)

respects from those of the Lake Superior region. The lower portion of the gorge is sunk into the Archæozoic gneisses. These are overlain unconformably by a strongly dipping series of sedimentary (Proterozoic) strata separated by minor unconformities, and they, in turn, underlie unconformably the Cambrian strata. Some measure of the length of time represented by the unconformities is shown by the flatness of the floor (Fig. 369) upon which the Proterozoic rests, and also of that above the tilted Proterozoic sediments upon which the Cambrian lies.

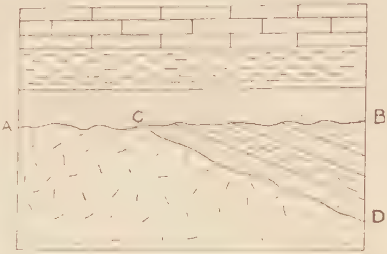


FIG. 369. — Section of the Grand Canyon of the Colorado River, Arizona. The lower portion shows the complex schists of the Archæozoic. Upon them, separated by an unconformity *CD*, rest a series of Proterozoic strata. The Proterozoic strata are separated from the overlying Cambrian by the unconformity *AB*. (See Fig. 368.)

In the Black Hills of South Dakota (Fig. 370, also see Fig. 342, p. 356), in the cores of many of the mountain ranges of the west, as well as in the Adirondacks and the Piedmont Plateau of eastern North America, Proterozoic rocks have been identified with some certainty.

Rocks of this age are believed to occur on other continents, but their correlation has not yet been definitely determined. In China, for example, the Pre-Cambrian rocks have a threefold division, the upper two of which are believed to be Proterozoic.

Fig. 370. — A generalized section through the Black Hills, South Dakota, showing the basal Archæozoic rocks underlying the Cambrian and younger strata.

Iron and Copper Deposits. — A discussion of the Proterozoic would be incomplete without mention of the valuable deposits of iron which they contain. In the five years previous to 1914, 216,981,280 long tons of iron ore were mined from the Proterozoic rocks of the Lake Superior region alone, making this the most important iron-ore center in the world. The ore, chiefly as hematite (Fe_2O_3), occurs in the form of thick beds in the sedimentary strata. Originally some of the formations contained large quantities of iron minerals intermingled with silica and other non-metallic minerals, and if it had remained in this state would probably not have been of commercial value. The iron ore was later concentrated through the agency of underground waters which dissolved out and carried away the silica and other impurities, leaving pure, or nearly pure, iron ore. Some deposits were further enriched by "replacement" (p. 372), ore being deposited as the non-metallic minerals were removed.

One of the greatest known deposits of native copper occurs in the rocks of the Keweenawan system of the Lake Superior region. The copper occurs in the cracks of igneous rocks, in the pores of some of the lava flows, and in the spaces between the pebbles and grains of sand of the conglomerates and sandstones. The copper was originally diffused in small quantities through the lava, but was partly dissolved out by underground water, carried into porous layers, and there deposited, in some cases in such quantities as to constitute a cementing material.

Life of the Proterozoic Era. — The indirect evidences of life in the Proterozoic are more abundant than in the Archæozoic, although of much the same character. Limestones imply but do not prove the existence of shell-bearing animals, such as are now forming the calcareous ooze and shell deposits of the ocean bottom. Graphite and black shales are suggestive of plant remains. The great deposits of iron ore are thought to indicate the existence of life, since organic matter seems necessary to have furnished the carbon dioxide by means of which the insoluble iron minerals were decomposed, and as soluble iron carbonates were carried away and redeposited where the further movement of the underground water was prevented. It is possible, however, that decomposing organic matter may not have been essential to this process.

FIG. 371. — An appendage of a crustacean (*Beltina danai*) from the Proterozoic. This is one of the oldest known fossils. (After Walcott.)

Direct evidence is furnished by a few fossils that have been found in the Proterozoic rocks of the Grand Canyon of the Colorado in Arizona, and in rocks of this age in Montana and Ontario. The known animal life consists of several species of worms, a large crustacean (Fig. 371), a sponge-like fossil (Atikokania),[1] some of which are 15 inches in diameter, and a brachiopod. Abundant fossils of a calcareous alga (Fig. 372), individuals of which are more than two feet in diameter, form layers of limestone three feet thick. It is probable that when all parts of the world become geologically better known, fossils will be discovered in Proterozoic formations as distinctive in character as those of the Cambrian and overlying systems.

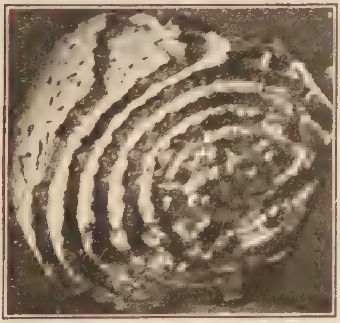


FIG. 372. — Hemispherical bodies believed to have been formed by blue-green algæ. Proterozoic, Montana.

Duration. — The fossils of the Proterozoic, though few and fragmentary, show that some forms of life were well up in the scale of life. Crustaceans, worms, and brachiopods (p. 414) are so high in the scale as to force the conclusion that life had been in existence many millions of years prior to this time. Moreover, judging from the extreme slowness with which evolutional changes take place, the great differentiation in the life proves a great antiquity. When this evidence, even though theoretical, is taken in connection with the great thickness of the sediments and

---

[1] *Atikokania* is probably not a sponge but a calcareous alga.

lava flows, as well as the long periods represented by the unconformities, it seems probable that the Proterozoic was very much longer than all of Paleozoic time. In fact, if the degree of life development is taken as a basis by which to measure time, it is thought that the appearance of the Cambrian fauna, although many millions of years ago, was a comparatively recent event.

Climate.[1] — Little can be said of the climatic conditions of this remote age. The presence of fossils in Montana, Arizona, and Ontario indicates a climate that was certainly not frigid. The presence of scratched bowlders in formations believed to be Proterozoic in Norway, Ontario, and Australia, and perhaps in southern Africa, sometimes resting upon a striated rock pavement possessing such characters as to make the glacial origin of the deposits undoubted, leads to the surprising conclusion that even at this time the earth was visited by periods of glaciation such as that of the Great Ice Age. There is some question as to the age of these glacial formations, some investigators believing that they belong to the Lower Cambrian. According to the theory of a cooling earth, with an atmosphere that was at first heavy, it is difficult to explain the presence of continental ice sheets in this early era.

Life before Fossils. — The earliest rocks in which an abundance of fossils of which any records have been found occur in the Cambrian.[2] These fossils are highly organized and are not the simple, unspecialized ancestors of modern animals that the theory of evolution demands. They are of a degree of specialization which indicates a long period of preceding life. Can the life which antedates the first known fossils be inferred?

In the seas of to-day the number and aggregate bulk of minute and microscopic soft-bodied animals and plants which live near or at the surface of the ocean is astonishing. Small jellyfish sometimes cover the ocean for many miles, tiny crustaceans live in myriads and microscropic animals in countless numbers. The reasons for the abundance of microscropic life near the surface (*i.e.*, within a few hundred feet of the surface) are evidently to be found in the abundance and uniform distribution of mineral food in solution, in the presence of sunlight, and in the uniformity of temperature. Practically all of the life of the ocean depends upon these simple forms, either directly

---

[1] Schuchert, Chas., — *Climates of Geologic Time,* Carnegie Institution of Washington, Publication 192, 1914, pp. 263–298.

Walcott, C. D., — Smithsonian Misc. Coll., Vol. 64, 1914, pp. 80–84.

[2] Unless the problematical Eozoön proves to be organic.

or indirectly. Yet, with the conditions as they are to-day, almost nothing of this profuse life would be preserved in a fossil state as a record of their existence, since, with few exceptions,[1] fossils are confined to such forms as possessed some hard parts, such, for example, as shells or skeletons. The study of embryology teaches that all classes of life were descended from minute, possibly swimming creatures. The starfish, coral, shellfish, and other marine animals all began life as minute, free-swimming forms. It seems probable that preceding the Cambrian the oceans were tenanted by such small, soft-bodied animals as those which populate the surface to-day, and that they were in equal abundance.

The question next to be answered is: Why did any of these animals seek the bottom of the ocean and become stationary forms? The first settlers on the bottom probably did not secure more or better food than their swimming relatives, but they had one advantage: they were able to devote their superfluous energies to growth and multiplication and thus to become larger and to increase in numbers faster than the swimming forms. Consequently those which first acquired the habit of resting on the bottom soon began to multiply faster than their swimming relatives. But this rapid increase must soon have given rise to crowding and competition which led to a struggle for existence. Thus the stronger forms increased at the expense of the weaker.

The development of hard coverings, such as the shell of the mollusk (the clam is an example, p. 413) and the crustacean (the crawfish is an example, p. 410), may have been due largely to such competition, since the animal which was protected in some way would have a better chance to escape being devoured. Or the development of hard protective coverings may have been due to the appearance of some especially voracious creature, and the trilobite (p. 410), the largest and most active of the inhabitants of the early ocean bottom, has been suggested as the aggressive animal. Later however, some animal arose more formidable and active than the trilobite, such perhaps as the ancestor of the fish, and may have caused the development of still heavier armor.

REFERENCES FOR THE PRE-CAMBRIAN ERAS

Adams, F. D., — *Basis of Pre-Cambrian Correlation:* Outlines of Geologic History (Willis and Salisbury), pp. 9–27.

Brooks, W. K., — *The Origin of the Oldest Fossils:* Jour. Geol., Vol. 2, 1894, pp. 455–479.

---

[1] Some jellyfish, worm borings, worm casts, trails, etc

Chamberlin and Salisbury, — *Geology*, Vol. 2, 1906, pp. 133–217.

Coleman, A. P., — *The Lower Huronian Ice Age:* Jour. Geol., Vol. 16, 1908, pp. 149–158.

Morris, Charles, — *Life before Fossils:* Am. Naturalist, Vol. 30, 1896, pp. 188–194; 279–285.

Ries, H., — *Economic Geology*, 3d ed., Iron Ore, pp. 364–371; Copper, pp. 402–405.

Schuchert, Chas., — *Climates of Geologic Time:* Carnegie Institution of Washington, Publication 192, 1914, pp. 263–293.

Steidmann, E., — *Summaries of Pre-Cambrian Literature of North America;* Jour. Geol., Vol. 23, 1915, pp. 81–92.

U. S. Geological Survey Folios.

Van Hise, C. R., — *Pre-Cambrian Geology of North America:* Bull. U. S. Geol. Surv. No. 360, 1909.

Van Hise, C. R., — *The Pre-Cambrian Rocks:* Outlines of Geologic History (Willis and Salisbury), pp. 1–8.

Van Hise, C. R., — *The Problem of the Pre-Cambrian:* Bull. Geol. Soc. America, Vol. 19, 1908, pp. 1–28.

CHAPTER XV

THE CAMBRIAN PERIOD

The Paleozoic Era. — Lying above the Pre-Cambrian formations is the Paleozoic group, which includes the following systems:

Younger Paleozoic Characterized by the presence of vertebrates, both fishes and amphibians	7. Permian	Carboniferous
	6. Pennsylvanian	
	5. Mississippian	
	4. Devonian	
Older Paleozoic Characterized by the scarcity of vertebrates	3. Silurian	
	2. Ordovician	
	1. Cambrian[1]	

The first three of these systems (the Cambrian, Ordovician, and Silurian) are sometimes grouped together as the older Paleozoic, since they are characterized by invertebrate life, vertebrate remains being absent in the first half and rare in the second half. The younger Paleozoic (Devonian, Mississippian, Pennsylvanian, and Permian) is characterized by the higher forms of life, such as fishes, amphibians, and reptiles, although invertebrates were as abundant as in the older Paleozoic. These seven periods[2] are not of equal length, nor are they of equal importance in the evolution of life, but may be recognized in any portion of the world in which they occur by their peculiar fauna. Locally, the systems are often clearly marked by unconformities (p. 270), but it is upon differences in the faunas that the separations are ultimately based (p. 417).

The maximum thickness of the Paleozoic rocks in Europe is estimated at 100,000 feet, and in the Appalachian region of this country a maximum up to 40,000 feet is exposed. The duration of the Paleozoic era was immense, exceeding that of all subsequent time.

---

[1] Ozarkian is a proposed system which includes the Upper Cambrian and part of the Lower Ordovician.

[2] Schuchert, Chas., — *The Delimitation of the Geologic Periods*, illustrated by the paleogeography of North America: International Geological Congress, 1913.

THE CAMBRIAN PERIOD

Divisions of the Cambrian. — The first great period of the Paleozoic is the Cambrian (Latin name for Wales), so-called because of its development in Wales, where it was first studied with care. This is the oldest fossiliferous system known at present (although a new series of fossils may yet be discovered in the youngest Proterozoic rocks), if one excepts the few fossils found in the Proterozoic; and upon it we must depend to a large extent for our knowledge of the early life of the world.

The Cambrian is usually separated into three subdivisions: the Lower (Waucobian), the Middle (Acadian), and the Upper (Croxian). These divisions are based upon differences in the character of the sediments in certain regions, but chiefly upon the differences in the faunas. A study of the fossils of the Cambrian formations has shown (as is true of all later systems) that the fossils of the earliest and latest formations of the system differ markedly, although some of them are the same. This is due to the gradual disappearance of some species and the introduction of others. Among the trilobites in the Lower Cambrian (p. 412) is a world-wide genus (Olenellus, Fig. 382 *A*, p. 412) which is not found in the Middle Cambrian, while in the Middle Cambrian a trilobite appears (Paradoxides, Fig. 382 *B*, p. 412) at about the time that the Olenellus drops out. The Upper Cambrian likewise is distinguished by the presence of another genus (Dicellocephalus, Fig. 382 *C*, p. 412). The fact that these trilobites are practically restricted to one series each has given rise to the use of their names in indicating the divisions of the system. Thus the life of the Lower Cambrian is spoken of as the *Olenellus* fauna, that of the Middle Cambrian as the *Paradoxides* fauna, and that of the Upper Cambrian as the *Dicellocephalus* fauna. Not only are certain trilobites characteristic of these three epochs of the Cambrian, but other forms of life as well, so that even though trilobites are absent, the age of the rocks can be determined by other genera and species. Although certain genera and species are practically confined to one formation, others have a wide vertical range, *i.e.*, are found in several formations. Such fossils, while showing that the rocks are of Cambrian age, do not, without the presence of those of more restricted vertical range, tell to which series they belong.

Location of Cambrian Rocks. — The Cambrian formations outcrop around the borders of the Pre-Cambrian rocks; as, for example, on the border of the Pre-Cambrian shield (p. 389) and the Pre-Cambrian mass of the Adirondacks, and in regions where the Cambrian has been exposed by the deep erosion of regions which have been raised and folded, as in the folded Appalachians, from the St. Lawrence to Alabama, and in portions of the West. For the most part, however, Cambrian rocks in North America, although of wide extent, are not exposed at the surface over large areas, being deeply buried under younger strata.

Fig. 373. — Map showing the probable distribution of land and water in North America during Lower Cambrian times. The shaded portion is land. The Lower Cambrian sediments were laid down in long, narrow straits. (Modified after Schuchert.)

Physical Geography of Ancient Periods. — The determination of the distribution of land and water in such remote periods as the Cambrian is very difficult, and at best the outlines of the continents, oceans, and seas are only approximately known. Maps of the kind shown here (Figs. 373, 374) are based upon several lines of evidence.

(1) When the fossils of a formation of known age are found to be of practically the same species in outcrops that are widely separated, it is assumed that the waters in which they lived were either connected by broad straits, or, if nothing points to a different conclusion, that they inhabited the same seas. If, however, they are found to differ widely in species in regions which may, for example, be less than fifty miles apart, although the conditions under which they lived were apparently the same,

it is assumed that the seas which they inhabited were separated by dry land or other barrier to their spread. Here, however, is an opportunity for error, since currents of cold water are favorable for one fauna, while in the warm waters of the same sea, a short distance away, a very different assemblage of animals may flourish. Such a distribution has often been reported from the seas of today. This objection is not as serious as at first appears, since during much of the geologic past climatic zones were probably not as well established as now.

FIG. 374. — Map showing the probable distribution of land and water in the Upper Cambrian. The shaded portions are land. (Modified after Schuchert.)

(2) The character of the deposits furnishes aid in determining ancient shore lines. If a certain formation is a conglomerate, it is evident that it was laid down at or near the shore, since only strong waves and currents, such as are effective in shallow waters, are able to move coarse gravel. Sandstones are also good indicators of shores, or at least nearness of land. Muds point to shallow seas, while limestones are indicative of seas of wider extent, with more distant shores in which the accumulation of lime carbonate from the remains of shell-bearing and coral-secreting animals, and that chemically precipitated, was built up with little intermixture of muds and sands.

(3) The above, as well as other evidences of which space will not permit mention, taken in connection with the distribution of the

formations as shown on geological maps, gives a clue to the extent of the continents and the positions of the shallow seas (epicontinental; Greek, *epi*, upon) which at various times in the past covered large areas of what is now land. These maps, showing the distribution of the land and water in ancient periods, must be considered as mere approximations, since (1) the absence of strata does not always prove the absence of seas in the past in any particular region, because if the strata had been laid down they might have been subsequently carried away by erosion. For example (Fig. 375), 80 miles from the nearest rocks of a certain age (Devonian) in Illinois, fossils of this age were found in a fissure in rocks of older age (Silurian), the strata of the former having been entirely eroded away. If this accidental discovery had not been made, there would have been doubt as to the extension of the seas in Devonian times. Also, in the buried extensions of strata there may be many interruptions where islands and peninsulas formerly existed. (2) Much of the strata is often buried deeply under younger formations, and its distribution in such regions is uncertain.

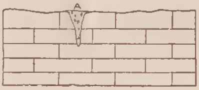


FIG. 375. — Devonian sediments, *A*, found in fissures of Silurian limestone. This is the principal evidence that Devonian strata at one time covered an area in Illinois.

Basal Unconformity. — The lower layers of the Cambrian formations usually rest upon the eroded surface of older rocks, showing that at the close of the Pre-Cambrian the continent of North America was probably even larger than at present. The comparative levelness of the Pre-Cambrian surface, except where it has been deformed by later movements, indicates that erosion had been active and that the land had been reduced to a comparatively level plain (peneplain, p. 114). Upon such a surface the sea appears to have gradually encroached. The reason for the spread of the water may be found either (1) in the actual sinking of the land or (2) in the raising of the sea level in an amount equal to the volume of the sediments which were being carried into the sea, displacing the water and causing it to overflow the land. As the sea encroached upon the land, it left upon its ancient surfaces the coarse gravels and sands composed of fragments of the older rocks, which occur at the base of the Cambrian system and constitute the "basal conglomerate."

Physical Geography of the Cambrian. — On evidence such as that already mentioned (p. 403), it has been found that at the beginning of the Cambrian (Fig. 373) the continent of North America was much expanded, the Atlantic shore being farther east than now. On the east a narrow sea stretched from Alabama northeast to Labrador, separated from the ocean by a land of unknown eastern extent called Appalachia, but whose western shore line was drawn near the site of the present Blue Ridge. In the west a similar sea existed which, at its greatest extent, reached from California to the Arctic Ocean.

The submergence of the continent continued in the Middle Cambrian, at which time a portion of the central United States was covered by seas whose shallowness is shown by ripple marks in the sandstone, and even by sun cracks made by the drying out of sediments exposed to the sun's heat. In the Upper Cambrian (Fig. 374) the seas spread over portions of the continent which were land in the Middle Cambrian and were withdrawn from others which had been covered by the Middle Cambrian seas, and in still other portions the sedimentation continued, showing that the seas remained as before. Consequently near the close of the Cambrian the physical geography was very different from that in the early epoch, the water covering a much larger area than in the latter.

Character of the Cambrian Rocks. — The Cambrian formations are composed of sedimentary rocks which vary in character from place to place. Where the sea advanced over a low shore in which there was an abundance of soil or other loose material, the waves and currents worked them over and spread them upon the sea bottom. Such was doubtless the origin of the Middle and Upper Cambrian sandstones which are so widespread in the interior of the United States. The occurrence of limestones and shales in the West and in the Appalachian Mountains indicates either that the shores were distant in these regions, or were so low that the gradients of the streams were insufficient to permit the latter to move any but fine material and such minerals as were soluble.

The thickness of the formations of the period varies from a few hundred to twelve thousand feet. This variation is due to the fact (1) that in some places deposition took place longer than in others, and (2) that in other places where erosion was rapid and the conditions favorable to sedimentation, the ocean bottom was built up rapidly by the sand and gravel brought in by the streams and waves. (3) In other regions, where the land was low, or (4) in portions of the seas distant from the shore, the sedimentation may have taken place with extreme slowness, so that in thousands of years the thickness of sediment accumulated was a small fraction of that laid down in an equal time in more favorable locations. This should be kept in mind in future discussions, since too often the student forgets that a comparatively thin formation may have required in its upbuilding as long or a longer time than a much thicker one of different material.

Present Condition of the Sediments. — Some of the Cambrian sediments have undergone important changes since their deposition. The gravels have been changed to hard conglomerates; the sands to sandstones, and where the quartz grains have been cemented by silica, into flint-like quartzites; the calcareous ooze of the clear seas into limestone. When metamorphism has been intense, shales have been converted into slates and schists, sandstones into schists, and limestones into marble. All of the Cambrian formations, however, have not been metamorphosed, some having been little changed. In many places the Cambrian strata have been intensely folded, tilted, and faulted (Fig. 376). Some of the mountain ridges of the Appalachians are formed of the hard, upturned edges of the quartzites of this age. In other regions, as in Wisconsin and northern Minnesota (Fig. 377), where the comparatively thin beds are not folded, the formations spread over a wide extent of territory.

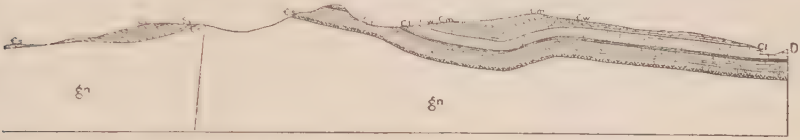


Fig. 376. — Section showing the relation of the Cambrian, *Cs*, and overlying strata to the Pre-Cambrian gneiss, *gn*. Crested Butte, Colorado.

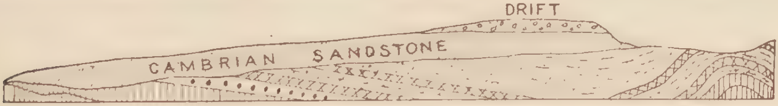


Fig. 377. — A section in northern Minnesota, showing the relation of the Cambrian to the Pre-Cambrian strata.

Volcanism. — The Cambrian seems to have been a time of little volcanic activity over the greater part of the world. In North America scarcely a trace of volcanic material has been discovered. Scotland and Wales, however, were the scenes of intense volcanic activity.

Close of the Cambrian. — The Cambrian is not separated from the rocks of the overlying system (Ordovician) by great unconformities, although local ones exist, but so gradual was the change that it is often difficult to draw a line between them. In fact, it has been suggested (Ulrich)[1] that the former dividing line be disregarded and the Upper Cambrian and a portion of the Lower Ordovician constitute a separate system called the Ozarkian.

Other Continents. — The Cambrian system is represented in Wales (20,000 feet) and Brittany by formations of great thickness. It also occurs in Scandinavia, Russia, Siberia, China, India, Australia, Argentina, and other parts of the world.

There appears to have been a land connection between North America and Europe, or at least a chain of islands separated by shallow water, in the Cambrian. This is shown by the strong resemblance of the fossils of this age in eastern North America and Europe, a similarity which would not have been possible had the animals inhabiting the shallow waters of the shores been unable to migrate from one continent to the other.

Life of the Cambrian

The richness of the life of the Cambrian is in marked contrast to that of the Pre-Cambrian, although the presence of worm trails and a highly developed crustacean (*Beltina danai*, Fig. 371, p. 397) in the latter indicates that the life of that ancient time comprised many forms of invertebrates. However, so few specimens have been found and so obscure is the evidence that little more can be said at present than that the facts indicate that life was well developed before Cambrian times began.

The apparently abrupt appearance[2] of the earliest known Cambrian fauna is probably to be explained by the absence on our present land areas of the sediments and fossils of the period between the Proterozoic and the Cambrian. This resulted from the continental area's being above sea level during the development of the unknown ancestry of the Cambrian fauna,[3] and consequently the sediments of that time are now covered by the sea and cannot be studied.

The indirect evidence of the existence of life long antedating the Cambrian is even stronger than the direct. A comparison of the life of the Cambrian with that of to-day shows that of the eight branches

---

[1] Ulrich, E. O., — *Revision of the Paleozoic Systems:* Bull. Geol. Soc. America, Vol. 22, 1911, pp. 281–680.

[2] Walcott, C. D., — *Abrupt Appearance of the Cambrian Fauna on the North American Continent:* Smithsonian Misc. Coll., Vol. 57, No. 1, 1910, pp. 1–16.

[3] The term fauna means the total animal life of a certain region or period.

of the animal kingdom all except the vertebrates have representatives in the former. If, as is generally believed, this differentiation was the result of slow evolutional changes, it is probable that a greater length of time was required to produce such a divergence than for all the changes in life that have taken place since the Cambrian.

Another indirect evidence is found in embryology. Each animal in its development from the egg to the adult condition passes through a series of stages which resemble those through which the *race* passed in its evolution, many embryonic stages representing those of mature but remote ancestors. It is evident, therefore, that the embryonic and larval stages of the individual furnish somewhat of a basis upon which to estimate the length of the evolutional history of the race to which the individual belonged. Some of the larval stages of the trilobites are preserved and give firm ground for the belief that this class had a long line of ancestors previous to the Cambrian.

Plants

Since all animals depend directly or indirectly upon vegetation for their food, it is evident that plants must have been in existence in large numbers in the Cambrian in order to supply with food the abundant marine animal life of that time. When, however, a search for plant fossils is made, few are found that can with certainty be recognized as plant remains. The inference is forced upon us that Cambrian plants were not highly organized, and that they possessed little or no woody tissue and were, consequently, incapable of fossilization. Some poorly defined, stemlike impressions found in the Cambrian strata at Burlington, Vermont, and elsewhere strongly suggest the stems of seaweeds, but some of these may be worm tracks; some, rill marks; and some, trailings made by animals. The difficulty in determining such "fossils" is well shown in the controversy over the determination of certain specimens (*Oldhamia*) found in the Cambrian rock of Ireland, which, as the illustration shows (Fig. 378), have the appearance of vegetable growth. Some investigators have classed them as the remains of animals, some as plants, and some as inorganic markings.

Fig. 378. — A problematical fossil, *Oldhamia antiqua*, which has been sometimes considered to be a plant.

The scarcity of plant fossils may perhaps be attributed to the fact that only Cambrian rocks of marine origin have been studied, since it is seldom, even in the sediments that are being deposited to-day, that plants are embedded in marine sediments.

Small calcareous algæ have been found in the Cambrian rock of the Antarctic Continent and elsewhere, and it appears probable that plants which secreted lime played an important part in the formation of the Cambrian limestone.[1]

ANIMALS

The oldest known fossiliferous rocks of the Cambrian contain a varied fauna. Corals, sponges, worms (in the form of trails and borings and impressions), brachiopods, pteropods, and crustaceans have been identified, and there is no doubt that the discoveries have brought to light only a fraction of the life of the time. Doubtless the lowly protozoans were in existence at that time, as well as other classes which have not been found. This diverse life, as has been shown, did not arise suddenly, but was derived from a long line of ancestors which lived during Proterozoic times.

Crustacea

Trilobites. — The highest and most striking form of life of the period was the trilobites (Greek, *tri-*, three, and *lobos*, a lobe or rounded

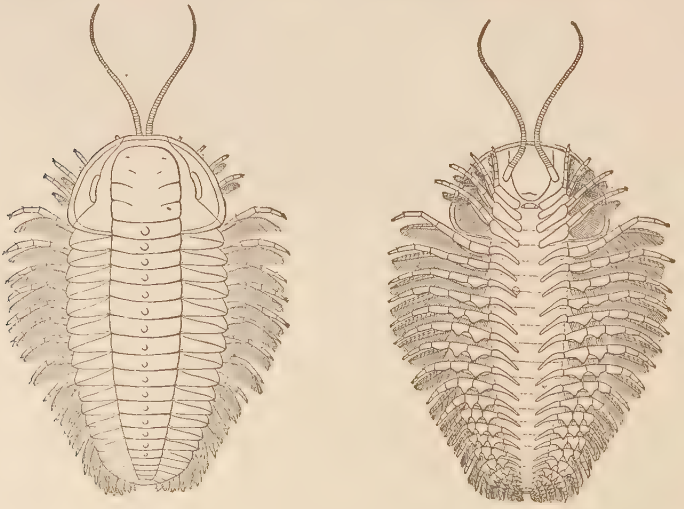


FIG. 379. — Dorsal and ventral views of an Ordovician trilobite, showing the restored appendages. (Beecher.)

---

[1] Garwood, E. J., — *Nature*, Vol. 92, 1913, p. 114.

projection), a group of animals belonging to the same phylum as the crabs and lobsters. The name trilobite is a very descriptive one, since the animal was marked by two grooves running lengthwise of the body, which divided it into three, usually well-marked lobes. Transversely, there were also three divisions: the head shield (cephalon); the body, composed of jointed segments (thorax); and the tail shield (pygidium). Trilobites were marine animals and had delicate antennules, doubtless for touch, and numerous legs and breathing organs (Fig. 379). They were probably able both to crawl and swim. Their trails and burrows show that they burrowed and pushed their way through the muds and soft sands. A series of tracks probably made by a trilobite is shown in Figure 380.

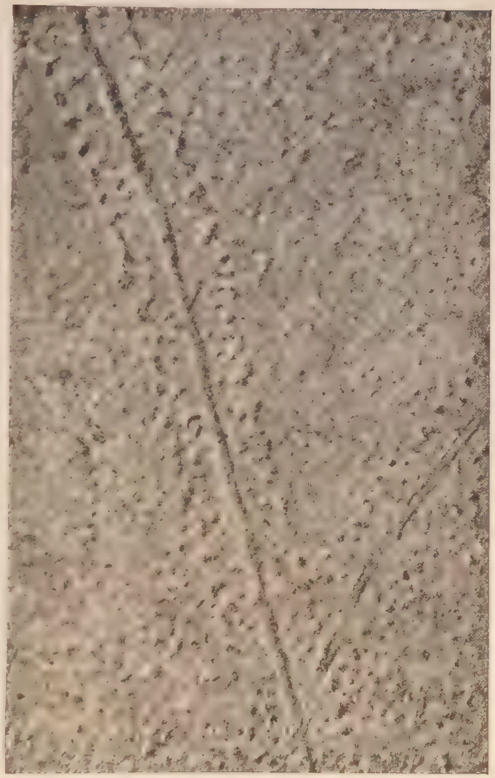


FIG. 380. — Tracks supposed to have been made by a trilobite.

The eyes of trilobites were usually raised, crescent-shaped elevations and were compound like those of an insect (Fig. 381), the number of lenses in each eye varying in different species from 14,000 to 15,000. A few species were eyeless. Cambrian trilobites (Fig. 382 *A*, *B*, *C*, *D*) varied greatly in size, in form, and in

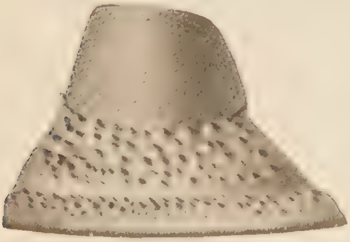


FIG. 381. — Eye of a Devonian trilobite, much enlarged, showing the many lenses forming the compound eye. (N. Y. Geol. Surv.)

ornamentation: some were a fraction of an inch long (Agnostus, Fig. 382 *D*), while others (Paradoxides, Fig. 382 *B*) attained a length of from one to two feet; some had a smooth surface and few body segments (two in Agnostus), while others were ornamented with spines and had a large number of body segments (Paradoxides had from 17 to 20); some had large eyes, while others were eyeless. These features show that the trilobite race must have extended far back into Pre-Cambrian times, since such a great diversity of form and structure could only be developed as a result of long evolution. Although trilobites varied greatly, it should be distinctly understood that in

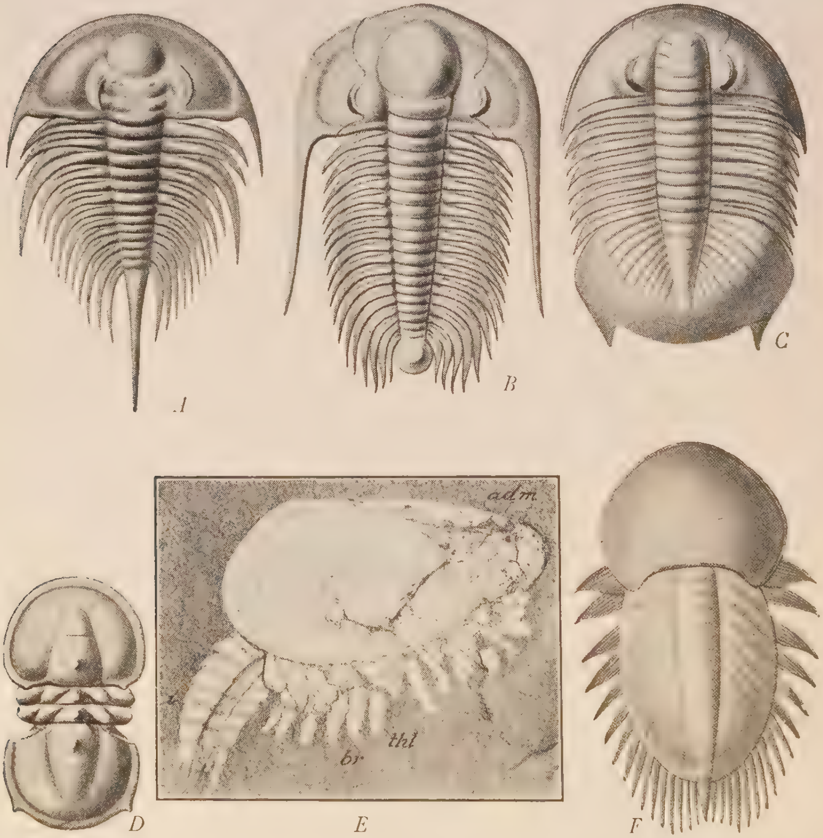


Fig. 382. — Cambrian crustaceans. Trilobites: *A*, *Olenellus thompsoni*; *B*, *Paradoxides harlani*; *C*, *Dicellocephalus minnesotensis*; *D*, *Agnostus interstrictus*. Other crustaceans: *E*, *Hymenocaris perfecta*; *F*, *Naraoia compacta*. (After Walcott.)

nearly every particular they were very primitive or simple in structure and closely agree with a theoretical crustacean ancestor.

Since trilobites moulted their shells at certain times and the great majority of their fossils consist of these fragments, a complete specimen usually indicates the death of an individual.

Not only were trilobites the most conspicuous animals of the period, but since new species and genera appeared, while the older became extinct, they furnish the best means of correlating the formations of different continents and of widely separated portions of the same continent. The three divisions of the system, as has been seen (p. 402), are consequently named for the three dominant genera of trilobites: the Lower or Olenellus zone, the Middle or Paradoxides zone, and the Upper or Dicellocephalus zone.

Other Crustaceans. — In addition to trilobites a number of crustaceans (Fig. 382 *E*, *F*) of a different group, representatives of which are living to-day, have been found in the Middle Cambrian of British Columbia. That a large and varied crustacean fauna preceded these is certain.

Mollusca

Gastropods (Univalves). — This class is now represented by snails, conchs, and winkles. The most conspicuous feature of the shelled forms is the single, usually spiral shell. Gastropods lived throughout the period but were seldom abundant. The earliest forms were chiefly simple, conical shells (Fig. 383 *C*, *E*), while later in the period coiled and spiral forms (Fig. 383 *B*, *D*) became more common. Some of the spiral forms bear a close resemblance to some modern gastropods.

FIG. 383. Cambrian gastropods: *A*, *Hyolithes carinatus*; *B*, *Pelagiella* (*Platyceras*) *primaevum*; *C*, *Scenella varians*; *D*, *Trochus saratogensis*; *E*, *Stenotheca rugosa*.

A division of the gastropods, the pteropods, was well represented in the Cambrian. The fossils usually consisted of simple, conical shells (Fig. 383 *A*). Several specimens have been discovered with distinct impressions of the characteristic fleshy portions.

Molluscoidea

Brachiopods. — This great class was especially important in the Paleozoic, not only because of the abundance of individuals, but also because certain species, though prolific, were short-lived, being abundant in one period or a subdivision of one period and becoming extinct at its close. As a result, when the fossil remains of such species are found in a stratum, proof is afforded of the age of the formation. Brachiopods or Lamp Shells (so-called because of the resemblance of some of them (Fig. 384 *A*, *F*) to Roman lamps) are inclosed by two shells or *valves* and can usually be readily distinguished from other shellfish by two characteristic features: (1) the bilateral symmetry of their shells, *i.e.*, a line drawn from the beak to the front divides them into equal parts; and (2), in most cases, by the dissimilarity and unequal size of the two valves. The name brachiopod (Greek, *brachion*, arm, and *pous*, foot) refers to the two long spiral "arms" inclosed between the valves by means of which food is obtained and respiration carried on. These "arms" are attached to a shelly apparatus, sometimes in the form of loops and sometimes in spirals (Fig. 403 *M*, p. 432).

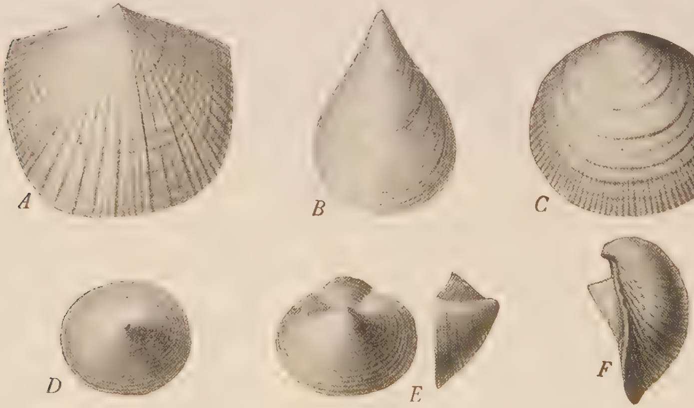


FIG. 384. — Cambrian brachiopods: *A*, *Billingsella coloradoensis;* *B*, *Lingulepis acuminata;* *C*, *Obolella atlantica;* *D*, *Acrothele subsidua;* *E*, *Micromitra bella;* *F*, *Kutorgina cingulata.*

Brachiopods are divided into two great subdivisions: the hingeless (Fig. 384 *B*, *D*, *E*) or inarticulate, with phosphate of lime shells the two valves of which were held together only by the muscles of the animal; and the hinged (Fig. 384 *A*, *C*) or articulate, with calcareous shells and well-developed hinges and dissimilar valves. Of these two subdivisions the first and most primitive was more abundant in the Cambrian, and the second, later in the Paleozoic. In the Lower Cambrian 22 genera of brachiopods have been found in Europe and North America, showing that the class was probably well-developed in the preceding era (Proterozoic). The two subdivisions of brachiopods are living in the seas of the present, having undergone many changes during their long existence; yet the class as a whole has been little modified since Cambrian times.


FIG. 385. — Cambrian cystoid: *Eocystites longidactylus.*

Echinodermata

Cystoids (Fig. 385) of very simple structure lived in the Cambrian, and *sea cucumbers* have been discovered in Middle Cambrian strata in British Columbia.

Worms

Perhaps the fossils next in abundance to the trilobites are the trails and borings of worms. In certain Lower Cambrian beds vertical tubes (Scolithus) are so common as to give a striped appearance to the rock. Many fossils which were at one time thought to be fossil marine plants are now known to be the trails of worms, or borings which have been filled with sand or clay. Since worms are, as a rule, destitute of hard parts, it is seldom that any traces of the actual animals have been preserved. In some fine shales of the Middle Cambrian in British Columbia, however, the fleshy parts of the animal are sometimes preserved as a glistening surface, even to the fine details of the structure (Fig. 386 *A*, *B*).

FIG. 386. — Cambrian worms: *A, Ottoia prolifica; B, Worthenella cambria.* These fossils are represented by a thin film which is darker than the shale containing them, the contents of the animal being preserved as a glistening surface. (After Walcott.)

Cœlenterata

Corals. — Cambrian corals (Fig. 387) were so simple in structure that some of them have been called sponges by certain writers and corals by others. This group was abundant locally, but in general was rare throughout the period.

Graptolites. — This group will be discussed more fully in the next chapter (p. 427), since it reached its greatest abundance and development in the Ordovician. The word graptolite (Greek, *graptos*, written, and *lithos*, a stone) is descriptive, since, when preserved in shale, as is usually the case, graptolites have the appearance of lead-pencil marks (Fig. 397, p. 428) with saw teeth on one or both sides. Graptolites were slender organisms, plant-like in appearance, usually resembling the modern hydroids. As is true of hydroids, they were composite animals in which the individuals lived in cells strung on one or both sides of a slender, horny axis which united the "colony." The form of these colonies varied greatly, as will be shown later (p. 428). Graptolites appear for the first time in the Upper Cambrian.

FIG. 387. — Cambrian coral: *Archæocyathus rensselæricus*.

Jellyfish. — The discovery of fossil jellyfish in Cambrian rocks is most surprising, since these animals have no bony skeletons or shells. Specimens preserving the external form as well as something of the interior structure have been found. They must have been buried in mud soon after they died, for otherwise they would have been destroyed by the worms and predatory crustaceans associated with them.

Sponges lived in some abundance in portions of the Cambrian and were represented by several genera. They are known by their siliceous spicules, which were either embedded in horny fibers or interlaced into a supporting framework, and which were preserved because of their resistant character.

Protozoa

Theoretically there is every reason to believe that the simple unicellular protozoa were as abundant in the Cambrian seas as in the present oceans, but few fossils have been discovered which are known with certainty to belong to this group.

SUMMARY

Evolution during the Cambrian. — It has been seen that at the beginning of the Cambrian many classes of animals were already in existence, and that the advanced stage of development of some of them, notably the trilobites, taken in connection with the traces of Pre-Cambrian life, indicates that life was well-advanced before Cambrian time began. Whether or not the evolution of this Pre-Cambrian life was rapid is not known. Evolution during the Cambrian was continuous, but more rapid at certain times than at others, the fauna at the close of the period being distinctly more advanced than that at the beginning. The evolution of life was profoundly influenced by environment, this perhaps more than any other cause being responsible for the marked difference between the faunas of the Lower and Upper Cambrian.

Since the life of the Cambrian changed from time to time during the period, a study of the fossils of any stratum, as has been said, gives definite information as to the relative age of the beds containing them. This change in the fauna was brought about (1) by the slow evolution of species when conditions were somewhat uniform; (2) by rapid evolution due to changes in environment, such as occurred when seas were enlarged, shore lines shifted, and new conditions of food and temperature imposed; (3) by competition resulting from the immigration of large numbers of new species from other regions, which caused the extinction of many species and the modification of others.

Climate and Duration. — The widespread occurrence of coral-like organisms in the Lower Cambrian and the vast numbers of individuals of various species of trilobites and other classes indicate a warm and more or less uniform climate. In fact, throughout at least the greater part of the period the character and distribution of the fossils imply nearly uniform climatic conditions over the entire world.

The duration of the Cambrian is to be expressed in terms of hundreds of thousands of years. The time required to remove and deposit thousands of feet of rock must have been enormous. If limestone is deposited on an average of one foot a century, it would require 600,000 years for the accumulation of the 6000 feet of Cambrian limestone of some portions of the West, omitting the time necessary for the formation of the thick sandstones of the same regions. Perhaps 1,000,000 years may be placed as the minimum duration of the period and 90,000,000 years as the maximum.

REFERENCES FOR THE CAMBRIAN PERIOD

WALCOTT, C. D., — *The Cambrian Faunas of North America:* Bull. U. S. Geol. Surv. No. 10, 1885.

WALCOTT, C. D., — *Studies in the Cambrian Faunas of North America:* Bull. U. S. Geol. Surv. No. 30, 1886.

WALCOTT, C. D., — *Fauna of the Lower Cambrian:* Tenth Ann. Rept., U. S. Geol. Surv., 1890, pp. 515–629.

WALCOTT, C. D., — *Cambrian Brachiopoda:* Mon. 51. U. S. Geol. Surv., 1912.

WALCOTT, C. D., — *Cambrian Geology and Paleontology:* Smithsonian Misc. Coll. Vol. 53, 1908, pp. 1–230; and Vol. 57, 1910, pp. 1–16, 231–431.

CHAPTER XVI

THE ORDOVICIAN PERIOD

THE system next younger than the Cambrian is the Ordovician.[1] The name Lower Silurian has been replaced by the above, although still occasionally used by writers.

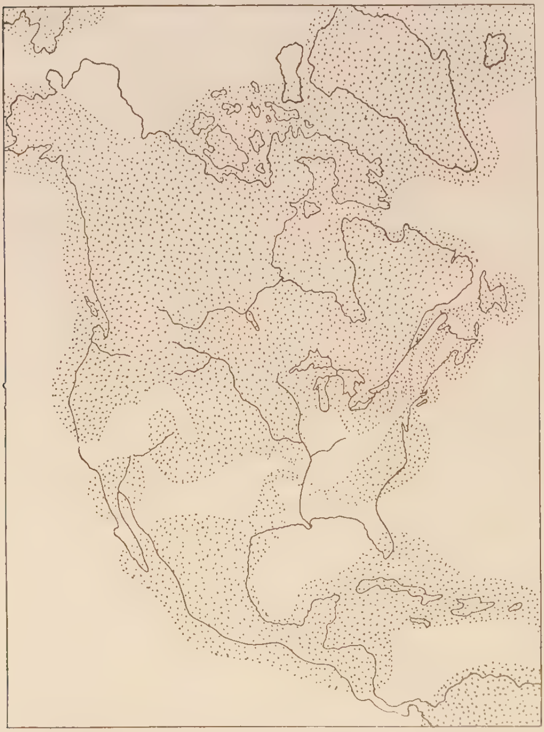


FIG. 388. — Probable distribution of land and water in the Lower Ordovician. (Modified after Schuchert.)

Ordovician Physical Geography.[2] — In North America during this period the epicontinental seas (p. 405) varied greatly in size and position in the different stages (Figs. 388, 389, 390, 391), shifting so often and to such an extent that an attempt to define their borders would require a more extended description than seems advisable.

In general, it can be said that the lands about the epicontinental seas were low and that the seas were shallow, as is

---

[1] *Ordovici*, an ancient tribe in Wales; a name given because the rocks of the period are well-developed in Wales.

[2] For the physical geography of the different epochs of this and subsequent periods the student is referred to Chas. Schuchert, — *Paleogeography of North America*, Bull. Geol. Soc. America, Vol. 20, 1910, pp. 427–606, which contains the most accurate maps of these remote periods.

shown by the character of the sediments, perhaps not exceeding 200 to 300 feet in depth. It is impossible to characterize the rocks of a system in a few words, since at all times in the earth's history sedimentary deposits of every description were being laid down in some portion of the world. This is also true of the Ordovician, during which gravels and sands were deposited in certain places, but limestones and shales form a much larger proportion of the deposits than perhaps in any other Paleozoic period. One of the physical conditions which brought this about was the limited area and probably slight elevation of the land, which consequently yielded little sediment, leaving extensive areas of the seas free from sands and muds. However, although built up largely of the remains of lime-secreting animals, such as brachiopods, corals, and bryo-

FIG. 389. — Probable distribution of land and water in the Middle Ordovician. The continent has probably never been so completely submerged since that time. (Modified after Schuchert.)

zoans, yet the lime was ultimately derived from the land by solution.

In the Appalachian trough (Figs. 392, 393), which was first formed in the Cambrian, sands, muds, and limestones were laid down. The Appalachian trough was separated from the Atlantic by the great island or continent of Appalachia, whose eastern extent was unknown. Its western border was a shifting shore which during certain times was west of the present Mississippi River. Sandstones occur in the West, where islands formerly existed, but are seldom extensive. In Newfoundland, Ontario, and west of the Adirondacks, limestone is the prevalent rock of the system, although shales are abundant, showing either that the land was low or covered by vegetation which prevented rapid erosion, or that the drainage of the land was not discharged in the direction of these regions.

FIG. 390. — A later stage of the Ordovician, when the land was greatly extended. (Modified after Schuchert.)

The Ordovician was a period of quiet, during which the epicontinental seas gradually increased until the middle of the period (Fig. 389), at which time a larger portion of the continent was under water than at any stage since the Pre-Cambrian, more than half of the continent being at this time submerged, the epicontinental seas, broken by peninsulas and large and small islands, extending at certain times from ocean to ocean. The seas were for the most part much less extensive in the latter part of the period (Fig. 390), at which time deposits of mud were laid down over extensive areas. A submergence almost equal to that earlier in the period (Fig. 389), however, again occurred (Fig. 391), and epicontinental seas spread widely over the continent. At the close of the period these seas were again drained, and the outlines of the continent were probably not unlike those of to-day.

FIG. 391. — A stage later than Fig. 390, when the continent was again greatly submerged. (Modified after Schuchert.)

FIG. 392. — A section through the Appalachian Mountains in Alabama: *Sc*, *Sr*, Silurian; *Dc*, Devonian; *Cb*, *Cl*, *Cp*, *Cw*, Carboniferous. (U. S. Geol. Surv.)

The classic section of the Ordovician in the United States is in New York, where it was first extensively studied.

Ordovician system	Pulaski stage (shale) Frankfort stage (shale) Utica stage (shale) Trenton stage (limestone) Black River stage including Lowville limestone Chazy stage (limestone) Beekmantown stage (limestone) Tribes Hill stage (limestone)

In this region limestone deposits prevailed during the Lower (Canadian) and Middle (Mohawkian) Ordovician, but shales in the Upper (Cincinnatian) Ordovician.

Close of the Ordovician. — The close of the Ordovician was marked by horizontal and vertical movements of considerable importance in eastern North America (Taconic deformation) and Great Britain. During the Cambrian and Ordovician in North America sediments had been accumulating in a subsiding trough lying between the Adirondack land mass and a land mass in New England, and which stretched from the St. Lawrence River to the City of New York and to the south (Fig. 374, p. 404). These sediments, after having been accumulated to a thickness of more than a mile, were subjected to great lateral pressure which folded them and brought them above sea level to form a mountain range of which the present Taconic Mountains of western New England are perhaps rather insignificant remnants. The folding was so intense that limestones were recrystallized to marbles, of which the most famous are those of Vermont and Massachusetts; the sandstones were changed to quartzites and schists, and the muds and shales to slates and schists. These disturbances affected the region east of the Taconics, but were comparatively local, as is shown by the slightly folded

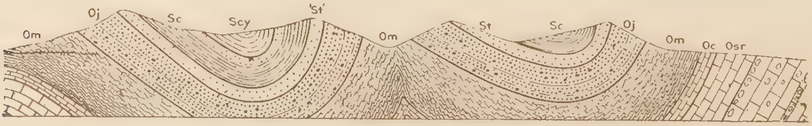


FIG. 393. — An east-west section through the Appalachian Mountains near Mercersburg, Pennsylvania, showing the relation of the Ordovician, *Osr*, *Oc*, *Om*, *Oj*, and the Silurian, *Sc* and *St*. (U. S. Geol. Surv.)

rocks of this period in New York, New Jersey, and Canada, only short distances from the scene of maximum deformation. The region north of the St. Lawrence seems to have been little affected, since the sedimentation continued from the Ordovician to the Silurian with slight interruption, almost the entire record being preserved in the strata of Anticosti Island in the Gulf of St. Lawrence. The date at which the Taconic deformation occurred is known, because the Silurian rocks rest upon the eroded and upturned edges of the Ordovician (Fig. 394), showing that after the deformation the strata were elevated and eroded for many years, and were again covered by the sea and Silurian deposits laid down on them. These disturbances, which culminated in the Taconic deformation and in the draining of the interior seas, were of long duration.

FIG. 394. — An east-west section in eastern New York, showing the Silurian resting unconformably upon the upturned edges of the Ordovician. (After W. J. Miller.) We have here the proof that this portion of the continent was raised above the sea during the Ordovician, and that after the land was eroded it sank, and upon this old land surface Silurian sediments were deposited.

Cincinnati Anticline. — The first evidence of a deformative movement in the Middle States is found in the formation of the Cincinnati and other anticlines, which appeared as low folds in the Middle Ordovician (Trenton). The Cincinnati arch, though later submerged, was again elevated and greatly enlarged at the close of the period. This fold extends over an oval area in Ohio, Indiana, and Kentucky, with the longer axis in a north and south direction.

The withdrawal of the epicontinental seas at this time may have been due to the sinking of the ocean bottoms (oceanic segments, p. 366) or to the raising of the land.

Volcanism. There is little evidence of igneous activity in North America during the period, although in England and Wales great masses of lava and volcanic ash form thick strata. Indeed the Ordovician volcanism of Great Britain was one of the most extensive in Europe since Pre-Cambrian times.

Ordovician of Other Continents. — Ordovician rocks occur in Great Britain, where a thickness of 24,000 feet has been measured. A deformation comparable to that in North America folded, crumpled, and metamorphosed the Ordovician strata at the close of the period. In Scotland the folding was exceptionally severe, producing overturned folds and faults, in one locality thrusting strata ten miles along a fault plane.

In Europe, although the Ordovician often underlies the Silurian unconformably, the disturbances which ushered in the latter appear to have been slight. On both continents the important disturbances took place where thick beds of sediment had accumulated.

Petroleum and Natural Gas

Conditions Favoring the Accumulation of Oil and Gas. — The importance of the oil and gas industry is such that the essential features of their geological occurrence demand attention.

Petroleum and natural gas occur in varying quantities in all of the fossiliferous rocks, from the Ordovician through the Tertiary, but oil never occurs in paying quantities unless there is a porous stratum overlain by an impervious one, in this respect resembling artesian wells. In an artesian well, however, it is essential that the porous stratum be open to the surface in order that the supply of water may be replenished. In an oil well, on the contrary, if the porous stratum reaches the surface the oil may be lost by evaporation, since the supply of oil comes from below.

Oil and gas usually occur at or near the crest of broad anticlines (p. 254) or other " reservoirs," where their further movement upward is prevented, the oil moving up the porous stratum through the water which permeates the bed, since oil and gas are lighter than the former. If, however, water is absent from the porous stratum, the oil will be at the bottom of the syncline and the gas in the anticline.

One of the modes of occurrence common in the eastern United States and Canada is shown in Fig. 395 *A*, in which the oil and gas gradually move *up* the bed until (1) the anticline is reached. If the stratum is saturated with water, the oil and gas will accumulate under the anticline, but (2) if water is absent, the oil will accumulate in the syncline (Fig. 395 *B*), while the gas passes on to the highest attainable point.

(3) Oil is accumulated also where the strata are domed up, as in Texas. The principle of the accumulation of the oil is the same as in the anticline. (4) In Mexico there are numerous volcanic necks

(p. 316) which have burst through the strata (Fig. 395 *C*), raising them and producing a dome-like structure which thus brings about favorable conditions for the concentration of oil. (5) Oil sometimes accumulates also where porous strata are faulted (Fig. 395 *E*) (California). The oil ascending along an inclined, porous layer is prevented from escaping to the surface by a fault which has displaced the strata to such an extent that the porous layer is sealed by an impervious one. (6) In Oklahoma big lenses of sandstone covered over by impervious beds (Fig. 395 *D*) sometimes yield large quantities of oil.[1]

The size of oil-producing regions is usually comparatively small.

Origin of Oil and Gas. — Petroleum has not a definite chemical composition, but is made up of a large number of substances (hydrocarbons), ranging from gases to solids, the gas in oil wells being merely a liquid that is volatile at low temperatures.

Since oil and gas are probably

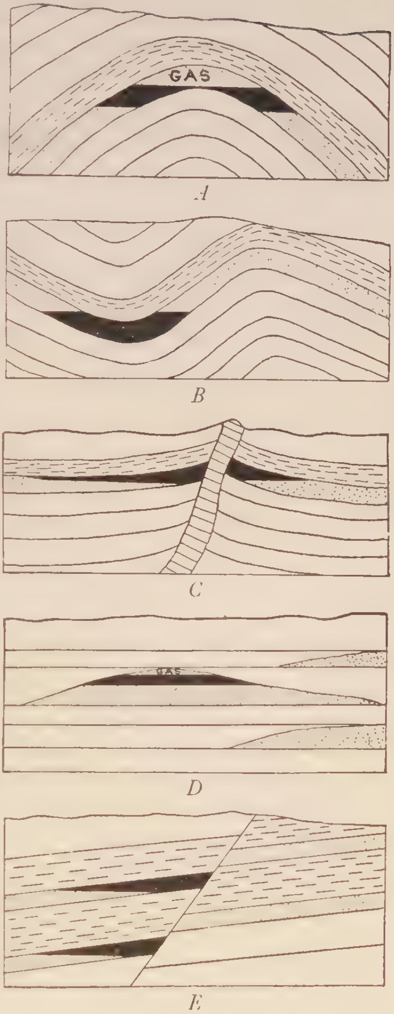


Fig. 395. — Diagrams showing the more important modes of the occurrence of oil and gas. Oil is represented in solid black. *A*, the oil-bearing stratum (dotted) contains water, and the oil and gas are consequently near the crest of the anticline (Pennsylvania and Illinois). *B*, the oil-bearing stratum is devoid of water. The oil is in the syncline. *C*, the strata are bent upward around a volcanic neck, and the oil has accumulated around the latter (Mexico). *D*, oil and gas occur in lenses of sandstone (Oklahoma). *E*, oil is accumulated as a result of faulting (California).

---

[1] Bosworth, T. O., — *Outlines of Oilfield Geology:* Geol. Mag., Vol. 9, 1912, pp. 16–24, 53–60. Clarke, F. W., — *Data of Geochemistry:* Bull. U. S. Geol. Surv. No. 491, 1911, pp. 681–704. Ries, H., — *Economic Geology*, 3d ed., pp. 50–100.

rarely indigenous to the rock containing them their origin has given rise to much speculation. There are two principal theories of the origin of oil, (1) the organic and (2) the inorganic, of which the former is more generally held. The inorganic theory is based upon laboratory experiments with metallic carbides, and holds that when water percolating downward through the earth's crust reaches heated rocks it becomes converted into steam which attacks the iron carbides, believed to exist there, generating hydrocarbons (oil). According to the organic theory, petroleum and its products are derived from animal or plant remains or both, which were embedded in the sediments and were later decomposed to oil. It is often stated that oil and gas were derived from beds of shale, either underlying or overlying the oil-bearing rock.

Life of Oil Wells and Fields. — The amount of oil yielded by single wells in various parts of the world in one day has exceeded 100,000 barrels, but such an enormous production lasts but a few weeks at the most. The oil wells of Pennsylvania have an average life of about seven years, those of Texas about four years, and those of California about six years. The average production of the wells of the Appalachian region was less than two barrels in 1907, and that of the California field was forty-two and a half barrels. Since the discovery of oil in the United States the production has increased from decade to decade, but this increased yield has been the result of the sinking of new wells and the discovery of new fields. The reason for the short life of oil and gas wells is that, unlike water, there is no perennial supply. The great spouting wells, or "gushers" are the fortunate tappings of the accumulations of ages which, though enormously productive when first opened, are also in about the same proportion rapidly exhausted.

Oil is more commonly found in the younger rocks than in the older, although some of the richest "pools" are in the Ordovician and Devonian. The reason for this seems to be that the older a formation is, the more opportunity there has been for the escape of the oil and gas (1) by faulting which permits the escape of the oil and gas from the porous rock, and (2) by the erosion of the edges of the oil-bearing strata when it is lost by evaporation. Only those Paleozoic strata which have been deeply buried and sealed by newer formations and have remained practically undisturbed are likely to yield large quantities of petroleum. The Ordovician limestones of Ohio have yielded large quantities of high-grade oil and gas; the Devonian sandstones of New York, Pennsylvania, and West Virginia, however, have furnished the richest oil-bearing strata of the eastern United States.

LIFE OF THE ORDOVICIAN

The life of the Ordovician differed from that of the Cambrian in the abundance of certain classes which were rare in the latter, and in the higher level of development in many cases. Graptolites, although rare in the Cambrian, attained their greatest abundance in the Ordovician. The primitive corals of the Cambrian were followed by well-developed forms; the cephalopods became the largest animals of the period; gastropods were much more modern in appearance; and brachiopods show a great increase in variety and abundance.

Protozoa

Siliceous protozoa (Radiolaria) are found in the Ordovician strata of some regions in sufficient numbers to show that they were abundant in the seas of that period.

Cœlenterata

Sponges are well represented by forms that secrete siliceous skeletons (Fig. 396 *A*, *B*), and some of them attained a diameter of a foot or more. Certain beds of the Ordovician (Chazy), of New York, are composed almost entirely of sponges.

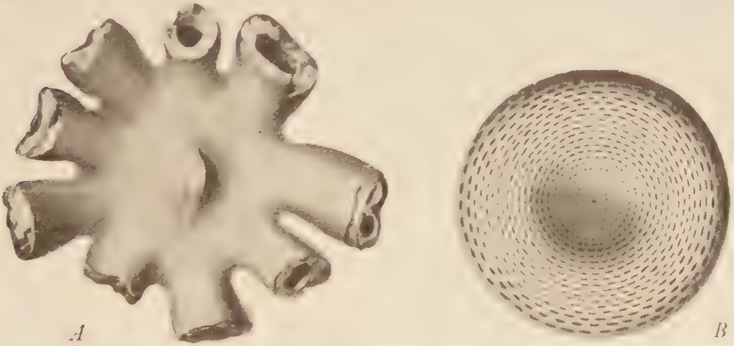


FIG. 396.—Ordovician sponges: *A*, *Brachiospongia digitata*; *B*, *Receptaculites ohioensis*.

Graptolites. —This class (Fig. 397 *A–K*) can be traced from its earliest appearance to its final extinction, through all the stages of development, and is consequently well-adapted to illustrate some principles of evolution.

Graptolites began in the Cambrian as small, bushy forms (Fig. 398 *A*) which, as a rule, lived throughout life attached to the sea bottom. Before the close of this period however, a change in the mode of life occurred which was to give the class entirely different habits and as a result bring about important modifications in the structure. For some unknown reason, perhaps to avoid a new creeping enemy, the colonies left the sea bottom. At first the branches of the bush-like colonies hung suspended, later they became horizontal, and still later the branches were turned upward. This change was accompanied by a reduction in the number of branches. The irregular many-branched early forms gave way to regular, many-branched colonies (Bryograptus, Fig. 398 *B*), then to eight-branched (Dichograptus, Figs. 398 *C* and 397 H), these, in turn, to four-branched forms (Tetragraptus, Figs. 398 *D* and 397 *K*), and these to two-branched forms (Didymograptus, Figs. 397 *A* and 398 *E*). In

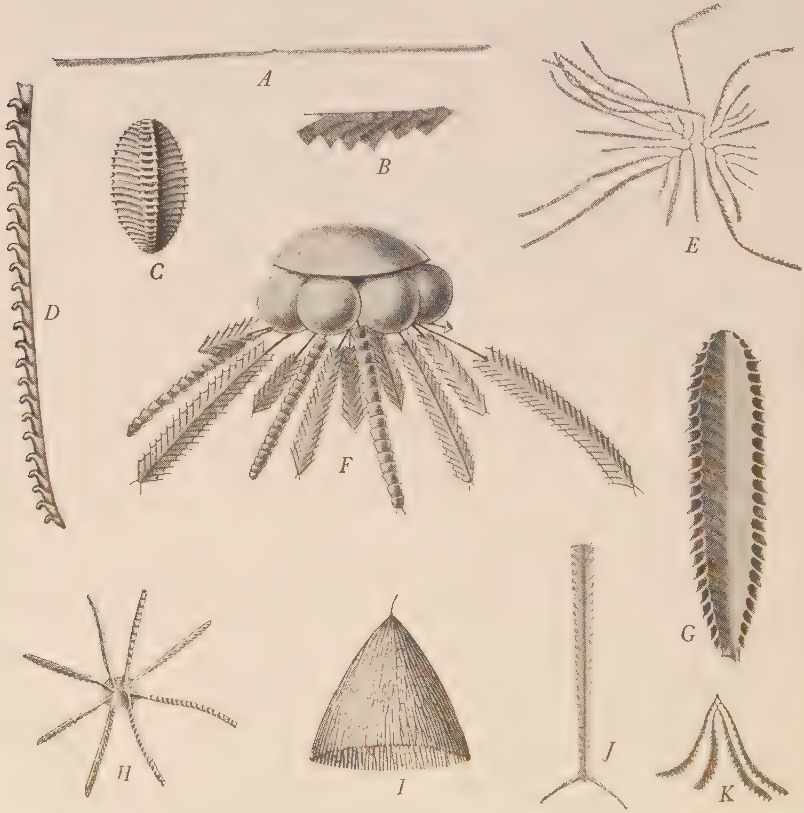


FIG. 397.— Graptolites: *A* and *B*, *Didymograptus nitidus; C, Phyllograptus typus; D, Monograptus clintonensis; E, Goniograptus postremus; F, Diplograptus pristis; G, Phyllograptus angustifolius; H, Dichograptus octobrachiatus; I, Dictyonema flabelliforme; J, Climacograptus bicornis; K, Tetragraptus fruticosus.*

addition to the changes in the main line of descent many aberrant forms came into existence, but were not long-lived.

Another important change in the race was brought about when the graptolites became detached from seaweeds and led an independent floating existence, being buoyed up by "floats" (Figs. 397 *F* and 398 *C*, *D*, *E*) to which they were attached by threads.

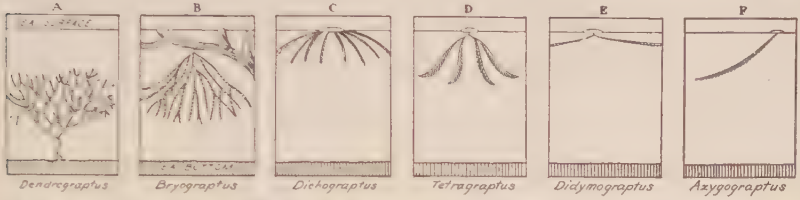


FIG. 398. — Diagram showing the evolution of one branch of the Graptolitoidea. At first attached to the sea floor, they later became attached to floating seaweeds and finally acquired floats. This change in their mode of life induced important changes in structure, one of which resulted in a reduction in the number of branches.

Towards the end of the race numerous spines appeared on some species, a network of protecting fibers was developed on others, and the colonies became small. They were on the defensive and soon disappeared. The forms which survived the longest were those inconspicuous ones which had remained attached to the sea bottom from the beginning of the race.

Because of the many progressive changes which the race underwent, and also because the colonies were carried about by currents over the seas of the world, graptolites are excellent fossils for correlating (determining identity of age) widely separated beds. The simple forms are especially characteristic of the Upper Cambrian and Lower Ordovician. The group in the main became extinct in the Silurian, but a few species lived even into the Carboniferous.[1]

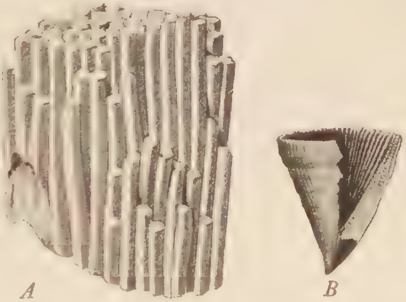


FIG. 399. — Ordovician corals: *A*, *Columnaria halli*; *B*, *Streptelasma profundum*. (A portion has been removed to show the interior.)

Stromatopora. — An extinct order of organisms known as stromatoporoids were especially abundant as reef builders in the Ordovician, Silurian, and Devonian. They were allied to the corals and consisted of colonies of minute polyps which secreted concentric layers of thin calcareous plates

---

[1] Ruedemann, R., — *Graptolites of New York, Part 2:* N.Y. State Museum, Mem. 11. 1908.

connected by vertical rods. Limestone masses, sometimes five by ten feet in horizontal extent and several inches thick, were built by them. The aggregate amount of limestone built by the stromatoporoids was very large.

Corals. — This class was present in the Ordovician and was represented by several types, among which were the simple, horn-shaped cup corals (Fig. 399 *B*) and those living in colonies (Fig. 399 *A*). The description of these types will be taken up under the Silurian (p. 444).

Echinodermata

Cystoids (Greek, *custis*, a bladder) were so named because of the bladder-like shape of the body. Essentially, the animals had a sack-like or bladder-like body made up of calcareous plates, on the upper side of which two arms were sometimes attached, while some species were armless (Fig. 400 *A–C*). The body was rooted by a tapering stem to the sea bottom. Cystoids first appeared in the Cambrian and reached their climax in the Ordovician and Silurian, after which they suddenly diminished in the number of species, although locally a few forms lived in considerable abundance. They are characteristic of the Ordovician and probably became extinct early in the Carboniferous.

FIG. 400. — Ordovician cystoids: *A, Lepidodiscus* (*Agelacrinus*) *cincinnatiensis; B, Pleurocystis filitextus; C, Amygdalocystites florealis.*

Crinoids (Greek, *crinon*, a lily) are living in the present seas and still constitute a vigorous stock, even though the race began in the Cambrian. The name "sea lily" was given to this class of animals because of their flower-like appearance. The animal (Fig. 401 *A–D*) consists of a body composed of plates, as in cystoids, and is attached to the sea bottom by a jointed stem. From the upper margin of the body (calyx) spring the arms, which are short and simple in some

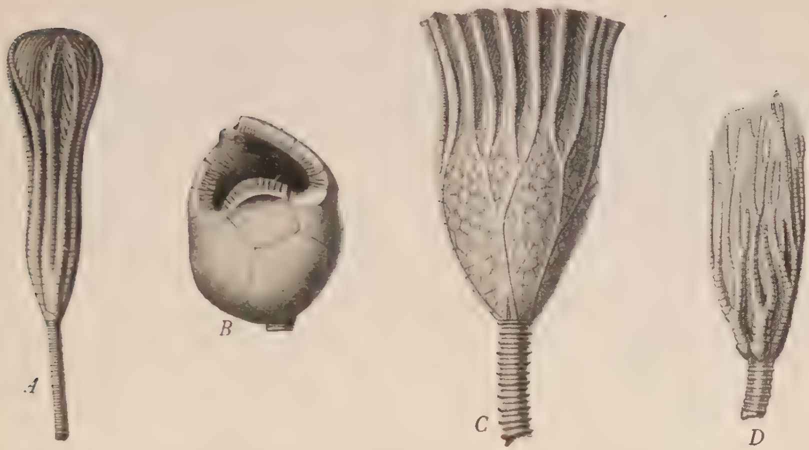


FIG. 401. — Ordovician crinoids: *A*, *Ectenocrinus grandis;* *B*, *Hybocrinus tumidus;* *C*, *Glyptocrinus decadactylus;* *D*, *Heterocrinus* (*Iocrinus*) *subcrassus.*

species and long and many-branched in others. Within the arms is the mouth, to which food particles are carried by the currents set in motion by the arms.

Blastoids, Starfish (Fig. 402), **Brittle Stars, and Sea Urchins** lived in this period, but as they were rare they will be discussed in later chapters. The origin of the starfish probably goes back to the Proterozoic, as may be inferred from the complex metamorphosis of the starfish larva. The absence of fossil starfish in the Cambrian sediments may mean that a preservable starfish skeleton was not evolved until the Ordovician.

FIG. 402. — Ordovician starfish: *Palæaster simplex.*

Molluscoidea

Brachiopods. — The preponderance of hinged (articulate) (Fig. 403, except *C* and *L*) species of brachiopods over hingeless (inarticulate) (Fig. 403 *C* and *L*) is very marked in the Ordovician. A conspicuous feature of many of the species was the greater thickness of the shells and the ribbing (Fig. 403, *F*, *G*, *H*) of the exterior by means of which the shell was strengthened. Brachiopods were very abundant and are important in determining the subdivisions of the series.

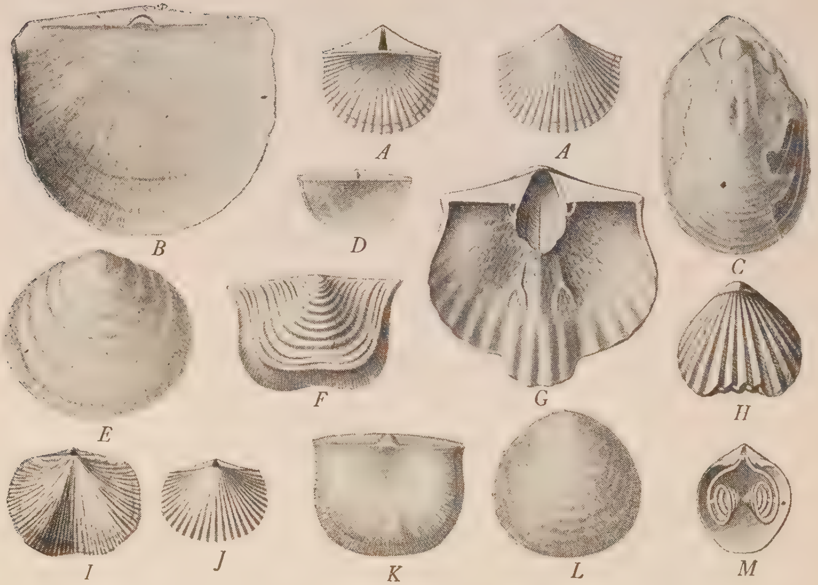


FIG. 403. — Ordovician brachiopods: *A*, *Orthis tricenaria;* *B*, *Raphinesquina alternata;* *C*, *Lingula rectilateralis;* *D*, *Plectambonites sericeus;* *E*, *Trematis ottawænsis;* *F*, *Leptæna rhomboidalis;* *G*, *Platystrophia lynx;* *H*, *Rhynchotrema capax;* *I*, *Dalmanella testudinaria;* *J*, *Hebertella borealis;* *K*, *Strophomena rugosa;* *L*, *Schizocrania filosa;* *M*, *Zygospira recurvirostris.*

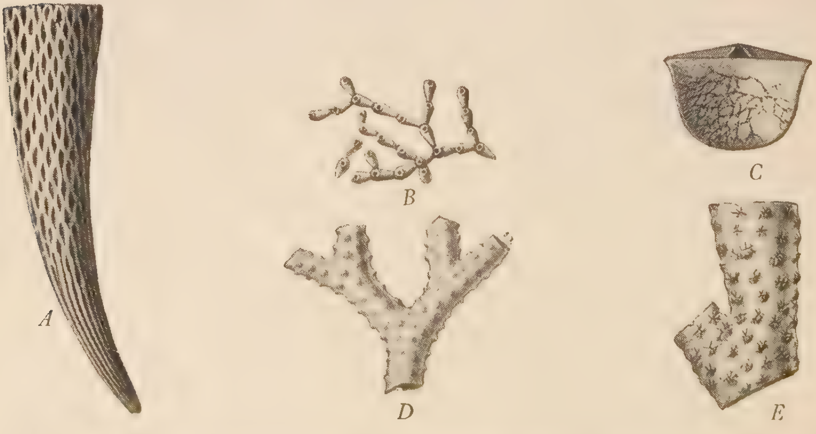


FIG. 404. — Ordovician bryozoans: *A*, *Escharopora subrecta;* *B*, *Corynotrypa inflata* (enlarged); and the same, *C*, in its natural position and size on a brachiopod; *D*, *Hallopora pulchella;* *E*, *Constellaria florida.*

Bryozoa. — Fossil *bryozoans* (Greek, *bruon*, moss, and *zoon*, animal) consist of small branching stems and lacelike mats (Fig. 404 *A–E*), the skeletons of minute animals that lived in colonies. They resemble certain corals in external appearance, but are related to the brachiopods. They can, as a rule, easily be distinguished from corals by the smaller size of the cells in which the polyps lived. Bryozoan fossils are very common in limestones of Ordovician age and were important limestone makers. They are valuable " index fossils " in determining the age of Ordovician strata, since they were abundant not only in individuals but also in species.

Mollusca

Pelecypods are abundant in the salt and fresh waters of the present, being represented by the clam, pecten, oyster, and many others. They have bivalve shells in which the two valves are usually nearly alike (Fig. 405 *A–E*). In external form they differ from brachiopods, which they resemble, in the lack of bilateral symmetry. Aside from fossils whose relationships are doubtful (Fordilla and Modioloides) this great class is almost unknown previous to the Ordovician. As a rule, pelecypods are rather rare fossils in the Ordovician rocks, being more abundant in sandstone and shales than in limestones, thus showing that they lived best on sandy and muddy bottoms.

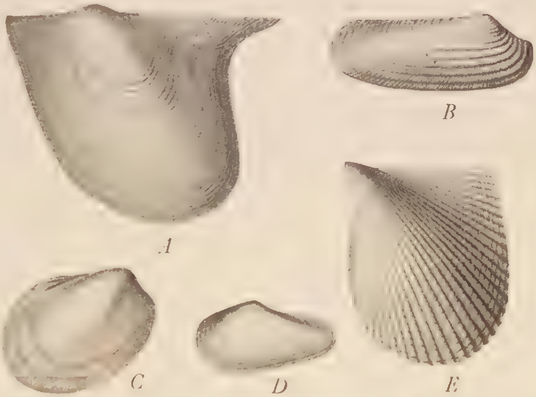


Fig. 405. — Ordovician pelecypods: *A*, *Pterinea demissa*; *B*, *Rhytimya radiata*; *C*, *Cyrtodonta billingsi*; *D*, *Ctenodonta nasuta*; *E*, *Byssonychia radiata*.

Gastropods. — This class was more abundant than the pelecypods, and even in the early Ordovician was represented by a considerable variety of forms (Fig. 406 *A–G*) which closely resemble modern relatives in external appearance.

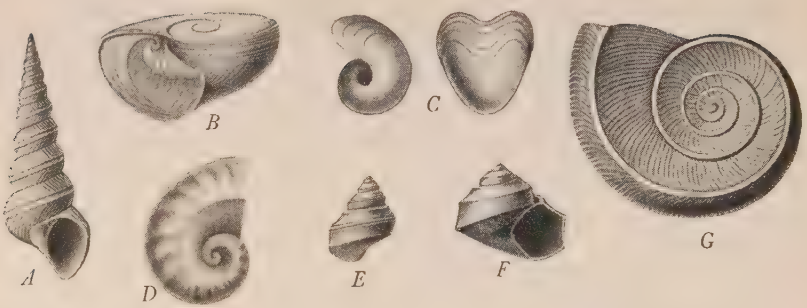


FIG. 406. Ordovician gastropods: *A*, *Hormotoma gracilis;* *B*, *Maclurea logani;* *C*, *Protowarthia cancellata;* *D*, *Cyrtolites ornatus;* *E*, *Lophospira bicincta;* *F*, *Trochonema umbilicatum;* *G*, *Ophileta compacta.*

Cephalopods. — This is the most highly developed class of the mollusks. All Ordovician cephalopods (Fig. 407 *A–D*) have shells such as those possessed by the nautilus of to-day. The shell is divided into a number of chambers by transverse partitions, called *septa*, through which a tube, the *siphuncle* (Fig. 407 *A* and *D*), extends from one end to the other, the animal living in the body chamber (Fig. 407 *A*) at the larger end. The juncture of the septa with the shell is called the *suture*, and, as will be seen (p. 528), the shape of this line is of great importance in determining the evolution of many genera. The shape and size of Ordovician cephalopods varied greatly,

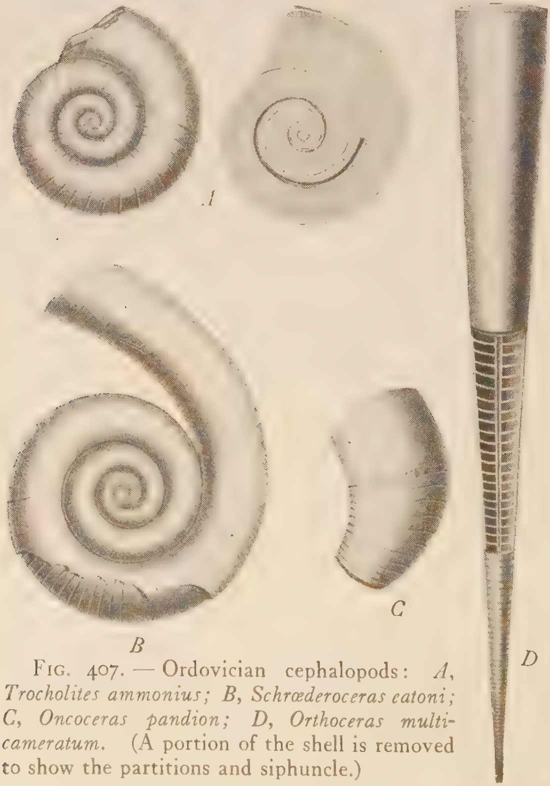


FIG. 407. — Ordovician cephalopods: *A*, *Trocholites ammonius;* *B*, *Schrœderoceras eatoni;* *C*, *Oncoceras pandion;* *D*, *Orthoceras multicameratum.* (A portion of the shell is removed to show the partitions and siphuncle.)

some being straight (Fig. 407 *D*), some curved (Fig. 407 *B*, *C*), and some tightly coiled (Fig. 407 *A*). The straight forms, represented by Orthoceras (Greek, *orthos*, straight, and *ceras*, a horn), were most characteristic of the period, some (Endoceras) attaining a length of ten or more feet and a maximum diameter of about one foot. At the other extreme were some less than an inch in length and one eighth of an inch in diameter. Cephalopods have been called the scavengers of the Ordovician, and they were probably the most powerful animals then living. The great diversity of the Ordovician cephalopods is evidence that the group began in the early Cambrian.

Crustacea

Trilobites. — The rapid evolution of the trilobites noted in the discussion of the Cambrian was continued in the Ordovician, during which

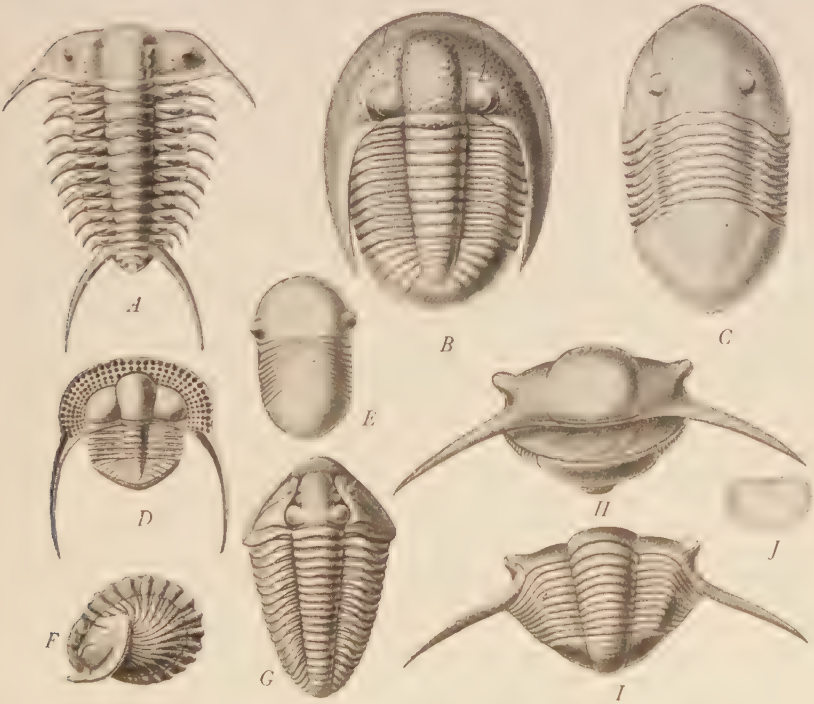


FIG. 408. — Ordovician crustaceans. Trilobites: *A*, *Ceraurus pleurexanthemus*; *B*, *Bathyurus longispinus*; *C*, *Isotelus gigas* (greatly reduced); *D*, *Trinucleus* (*Cryptolithus*) *tessellatus*; *E*, *Bumastus trentonensis*; *F*, *G*, rolled and straight specimens of *Calymene callicephala*; *H*, *I*, two views of a rolled specimen of *Thaleops ovata* Ostracod: *J*, *Leperditia inflata*.

period the class attained its greatest development (Fig. 408 *A–I*), more than half of all the known genera of trilobites being represented at that time. During the remainder of the Paleozoic they gradually declined until their extinction was reached in the closing stages. When Cambrian and Ordovician trilobites are compared, it is seen that the latter have rounder eyes, that the tail shield (pygidium) is larger, and that they have acquired the ability to roll themselves up (Fig. 408 *F*, *H*, *I*) and thus protect the lower portions of the body, many being found in this position which was apparently taken at the approach of death. The Ordovician trilobites as a rule were not so large as some Cambrian species, although a specimen 27.5 inches long has been found in Ordovician rock.

Other Arthropods continued from the Cambrian. *Ostracods* (Fig. 408 *J*), small bivalve crustaceans, flourished during portions of the period, and also *eurypterids* (p. 449).

Fishes

An important addition to the fauna of the Ordovician, and one which had a profound effect on the evolution of life in subsequent ages, was the fishes, remains of which have been found in Colorado and Wyoming.

FIG. 409. — Ordovician plants (*Sphenophycus latifolius*). They are probably appendages of floating algæ.

PLANTS

Seaweeds. — Our knowledge of the plants of the Ordovician is almost as incomplete as that of the Cambrian. No land plants have been found and no marine plants higher than seaweeds (Fig. 409) and calcareous algæ. The absence of land plants in Ordovician strata, however, does not prove that a land vegetation was lacking, since the known plant-bearing strata are all of marine origin and consequently the absence of land plant fossils would not be remarkable, even though land plants had been abundant.

SUMMARY

Progress and Character of Ordovician Life. — The life of the period as shown by the fossils was fuller, more varied, and of a higher grade than that of the Cambrian. Trilobites, cephalopods, gastropods, pelecypods, cystoids, graptolites, and corals became diversified and of higher types; and bryozoans, crinoids, and fishes are known for the first time. During this period graptolites and cystoids attained their climax and were never again important. In this period, too, the straight cephalopods rapidly developed from small to gigantic forms and into many species, but occupied a subordinate place after the Silurian. Before the close of the period all of the great types of life and most of the important subdivisions were present.

When the faunas of the Ordovician stages of North America are compared with those of Europe, it is found that, although the genera are usually identical, the species are different though similar.

Adaptation to environment was almost as well established then as now. Certain species lived almost exclusively on muddy bottoms, certain ones on sandy, and still others on calcareous bottoms. There was also adaptation to shallow and deep water.

The effect of isolation is noticeable when, for example, a portion of an epicontinental sea was cut off by some barrier, such as a gentle upfolding of a portion of the sea bottom, or a bar, or when ocean currents, because of their lower or higher temperature, prevented the life of different portions of the sea from mingling, the isolation of the fauna permitting an independent development without interference from outside. It consequently sometimes happened that the faunas of adjoining seas differed considerably. When the barriers were removed, a rapid and marked change in the fauna was often quickly brought about.

The evolution of the life of the period gave rise to many new species, with the result that when the fauna of the earliest and latest Ordovician are compared, they are found to differ widely. It is because of the appearance of new species that the Ordovician series of strata have been divided into several stages, which are usually easily distinguished by their contained fossils.

Climate and Duration of the Ordovician. — Fossils found in Ordovician strata of Arctic lands show that the climate there was not unlike that of the temperate and tropical regions of the same time. During the Middle Ordovician, and again later in the period, reef corals were common from Alaska to Texas. The conclusion is that climatic zones did not exist, but that the climate of the world was uniformly equable and less diversified than now.

The duration of the period was about the same as that of the Cambrian, perhaps 4,000,000 years.

REFERENCES FOR THE ORDOVICIAN PERIOD

BLACKWELDER AND BARROWS, — *Elements of Geology*, pp. 339–348.

CHAMBERLIN AND SALISBURY, — *Geology*, Vol. 2, pp. 304–367.

GRABAU AND SHIMER, — *North American Index Fossils*, Vols. 1 and 2.

SCHUCHERT, CHAS., — *Paleogeography of North America:* Bull. Geol. Soc. America, Vol. 20, 1910, pp. 485–489.

SCOTT, W. B., — *An Introduction to Geology*, pp. 560–577.

ULRICH, E. O., — *Revision of the Paleozoic Systems:* Bull. Geol. Soc. America, Vol. 22, 1911, pp. 281–680.

CHAPTER XVII

THE SILURIAN[1] PERIOD

THIS system has been divided into a number of subdivisions which in New York are as follows:

Rondout water lime
Cobbleskill limestone
Salina shales, salt, water lime
Lockport and Guelph dolomites
Rochester shale
Clinton shale, sandstone, limestone, and iron ore
Medina and Oneida sandstone and conglomerate

In eastern North America the Silurian strata, for the most part, rest unconformably upon the deformed and eroded Ordovician rocks. In the Middle States the Lower Silurian is usually absent, and the Middle Silurian strata rest unconformably upon the Ordovician or upon older rocks, showing that during early Silurian times the central portion of the continent was land. In Montana and Utah the strata of the Ordovician, Silurian, and Devonian are apparently conformable, and their separation is more or less arbitrary because of the scarcity of fossils.

Geography of the Silurian. — The period can, for convenience, be divided into three epochs. (1) During the first (early lower) the epicontinental seas were apparently restricted to three principal bays (Fig. 410): one stretching up the Mississippi Valley to northern Illinois; a second extending across Newfoundland and northern New Brunswick; and a third occupying the Appalachian trough, and stretching east and west over central New York and Ontario. Later in the Lower Silurian the seas were, for a time, withdrawn from the Appalachian trough and New York. (2) The middle (later lower) of the period (Fig. 411) saw an expansion of the seas over a large portion of Canada to the Arctic Ocean and over the United States east of the Mississippi River, and an extension of two seas on the west, one from California

---

[1] The name Silurian has been taken from the Silures, an ancient tribe which dwelt in Wales

through Idaho to Canada and another from Mexico into Arizona and New Mexico. It was during this time that the great limestone strata (Niagaran) were deposited. (3) The epicontinental seas were again restricted in the Upper Silurian (Fig. 412), the most important of them extending from Wisconsin and Illinois through New York and over the Appalachian trough. The three subdivisions of the period are therefore characterized (1) by constricted seas, (2) by expanded seas, and (3) by a later shrinking and shifting of the seas. It should be pointed out in this connection that Silurian strata do not cover all of the areas shown in the maps (p. 403), but often lie only in widely separated patches which appear to be remnants of a once continuous formation. The age and correlations of these patches are determined by their contained fossils.

FIG. 410. — Map showing the probable outline of North America during a portion of the Lower Silurian. (Modified after Schuchert.)

The sediments which were deposited in the Appalachian trough were derived from the broad island or continent of Appalachia (p. 406).

Character and Thickness of the Sediments. – Limestones are the common strata of the Silurian, but in eastern North America conglomerates, sandstones, and shales predominate. These latter were deposited in shallow seas, as the ripple marks and cross-bedding show. The formation and distribution of these coarse sediments teach an important lesson. Along the western boundaries of the eastern lands, gravel and sand were carried by rapid streams flowing from the areas newly raised by the Taconic deformation (p. 422) and were spread along the shores, forming wide beaches, the gravel (forming the Oneida conglomerate) rapidly thinning toward the west. Sand (Medina) was carried farther out into the sea by the currents and formed extensive sandstone strata. When in the course of time the lands were worn down, the streams were unable to carry such large quantities of coarse sediment as formerly, and the belt of gravel along the shores was consequently narrowed and sand was deposited nearer shore and upon the earlier gravels. It is evident from the above that the conglomerates and sandstones were contemporaneous. A still greater lowering of the land, either by erosion or by subsidence, further reduced the capacity of the streams for cutting, and during one epoch lime ooze (Niagaran) and during another mud (Salina) accumulated on the sandstones and conglomerates. Where the conglomerates have been tilted by later folding and cut by erosion, their upturned edges form mountain ridges.

FIG. 411. — Map showing the probable outline of North America during a portion of the Middle Silurian. (Modified after Schuchert.)

The Silurian formations west of New York are largely limestone, in portions of which well-developed coral reefs are to be distinguished. The falls of Niagara are due to the presence of a massive layer of limestone of Silurian Period, from which an important stage, the

Niagaran, received its name. The limestone of this stage is thickest in the Mississippi Valley, where it probably had been accumulating for a longer time than in New York. Such a great thickness of limestone indicates a long period during which few oscillations in level occurred, and when the lands were so low that little sediment was carried to the sea.

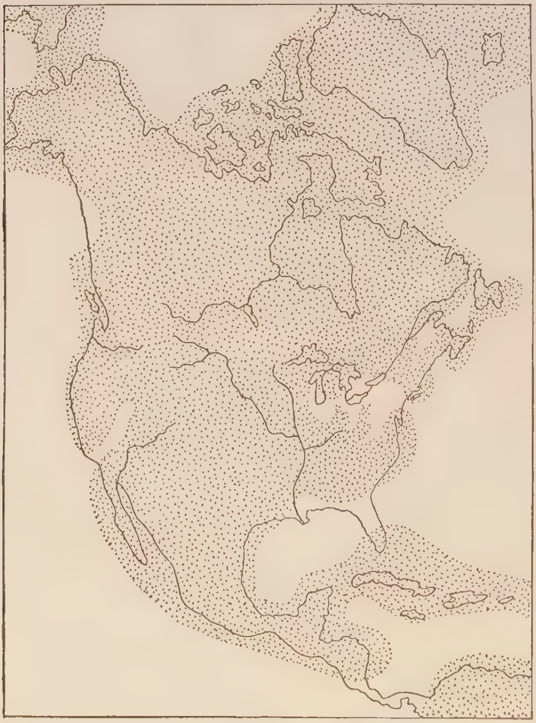


FIG. 412. — Map showing the probable outline of North America during a portion of the Upper Silurian. (Modified after Schuchert.)

The thickness of the Silurian in Maryland is about 3000 feet; in western Tennessee, about 1500 feet; in Alabama, about 500 feet; in central Tennessee, 300 feet; in Wisconsin, about 800 feet; and in Nevada, about 1000 feet.

Clinton Iron Ore. — One of the most widespread iron ore deposits known was accumulated during the Clinton epoch of the Silurian Period. It outcrops in one or more broken belts from New York, through Pennsylvania to Alabama, and occurs in beds at different horizons in the formation, sometimes as many as four beds being present in one locality. The thickness of the ore beds varies from 40 feet to a fraction of an inch, but a bed 10 feet thick is unusual. The ore is called " fossil " and " pea " ore because fossil fragments are commonly found in it with the shell substance entirely replaced with hematite, while some beds are made up of rounded grains of an oölitic character. The ore was deposited close to shore, probably in lagoons and marshes, and was probably a chemical precipitate, the iron having been brought to the sea by streams which had leached it from the igneous rocks over which they flowed.

The presence of iron ore, limestone, and coal within short distances of each other near Birmingham, Alabama, has made that city a great center for iron and steel industries. Coal is necessary to reduce the iron, and limestone is used as a flux to carry away the siliceous impurities.

Deserts. — During a portion of the Silurian (Salina) in eastern North America the climate was arid and desert conditions prevailed. This is shown by the beds of salt and gypsum, and by the red color of the shales. In New York state 325 feet of solid salt have been penetrated by wells. These salt beds are lens-shaped, and the conditions under which they were deposited may not have been unlike those to-day in the region of the Caspian Sea, the Dead Sea, and Great Salt Lake, or back of bars as described below. Such an arid climate may have been produced by high lands to the south and east, which shut off the moist winds from the Atlantic and the Gulf of Mexico.

Origin of Rock Salt. — Salt is primarily formed by the evaporation (p. 135) of the salt water of lakes or the ocean, and is accumulating to-day in certain salt lakes which have been greatly concentrated. The evaporation of inland salt lakes does not, however, seem adequate to produce thick beds of pure salt such as occur in certain regions.

The theory which best explains the origin of massive salt deposits assumes that a body of ocean water had been shut off partly or completely by a low bar. If the region in which this occurred was arid, the evaporation of the water back of the bar would exceed that carried in by the rivers and that derived from the ocean. The lowering of the water of the bay by evaporation would permit the ocean water to flow in if the bar were incomplete; if, however, the bar were complete and the bay entirely shut off from the ocean, forming a lake, ocean water would enter only during storms or at high tide. In time, the concentration of the water would be so great that common salt and other salts would be precipitated. Under conditions such as those outlined above, pure salt might accumulate to a considerable thickness without the admixture of mud. Occasionally, the purity of the salt might be broken by sheets of mud brought in by streams swollen by the torrential showers of desert regions.

The Silurian salt of New York seems to have been deposited either in extensive salt lakes or in an arm of the sea which was partially shut off from the sea by a bar.

Igneous Rocks. — The Silurian was a period of quiet as far as volcanism was concerned. In North America some igneous intrusions of this age are known, but they are not extensive.

Other Continents. — The Silurian epicontinental seas of Europe were extensive and had much the same position as in the Ordovician. Two distinct seas, one in the north and the other in the southern part of the continent, were separated by a land ridge. The life of the two seas was unlike in many particulars, that of the northern sea being typical of the period in other continents, while that of the southern had many peculiarities which indicate that it was partly isolated.

LIFE OF THE SILURIAN

Aside from a notable increase in the number and variety of corals, crinoids, brachiopods (spire bearers), and eurypterids, and a decrease in the graptolites and straight cephalopods, the life of the Silurian did not differ greatly in general aspect from that of the Ordovician. When, however, one looks for identical species and genera, he finds that the change was a marked one.

Cœlenterata

Corals forged ahead and became important in the Silurian. Instead of the few, usually simple forms of the Ordovician, a varied and abundant coral fauna, many of the corals compound, throve in the clear seas of the time. Four well-marked types were abundant: (1) *chain corals* (Halysites, Fig. 413 *A*), made up of vertical tubes joined together in such a way as to give them the appearance of a linked chain. Since chain corals began in the Ordovician and became extinct in the basal Devonian, their presence in a formation shows it to be either Ordovician or Silurian. (2) *Honeycomb corals* (Favosites) were composed of six-sided parallel columns, like a honeycomb, which

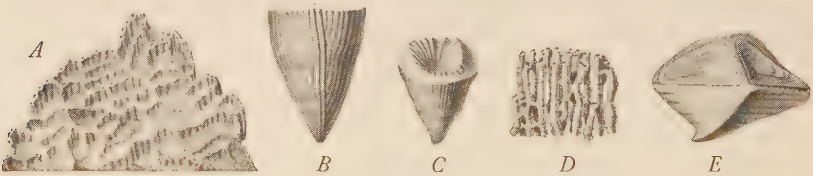


FIG. 413. — Silurian corals: *A*, chain coral, *Halysites catenulatus*; *B* and *C*, cup corals, *Streptelasma* (*Enterolasma*) *calicula*; *D*, *Syringopora retiformis*; *E*, *Goniophyllum pyramidale*.

were divided by horizontal partitions. Honeycomb corals were rare in the Ordovician, but built coral reefs in the Silurian and Devonian. (3) *Cup corals* (Enterolasma, Fig. 413 *B*, *C*, *E*) were horn-shaped, with a depression in the top. A peculiar cup coral of the period (Goniophyllum, Fig. 413 *E*) was provided with a cover which consisted of four triangular plates, hinged to the margins of the cup. The covering was evidently for protection against enemies, but since the genera which possessed it have no living representatives, it is probable that the device was not successful. Cup corals occurred in the Ordovician and continued until the close of the Paleozoic; many of these were separate individuals, while some were in hemispherical colonies (Fig. 451 *A*, p. 480). (4) *Organ-pipe corals* (Syringopora, Fig. 413 *D*) were similar to chain corals, but their cylindrical columns were not attached along their entire length.

Coral reefs date from the later Ordovician. Before this time simple corals predominated, and even these were rare. When, however, compound corals such as the honeycomb became abundant, the limestone secreted by many generations, together with that of associated animals such as brachiopods, gradually built up reefs at short distances from the shores. Silurian coral reefs were seldom of great thickness.

Other Cœlenterates. — *Stromatopora* were important reef builders, but *graptolites* no longer played an important rôle in America, and by the end of the period were practically extinct. *Sponges* (Fig. 414) are common in certain beds, the peculiar family *Receptaculites* (Fig. 414 *B*) which began in the Ordovician being not uncommon in some localities.

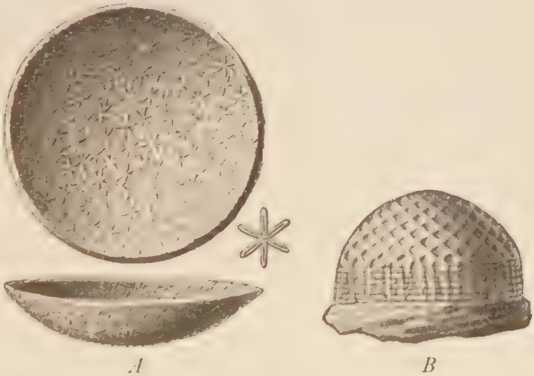


Fig. 414. — Silurian sponges: *A*, *Astræospongia meniscus*, two views; *B*, *Receptaculites oweni*.

Echinodermata

Crinoids (Fig. 415 *A*, *C*) became so numerous in the Silurian that their "joints" constitute an important part of the beds of certain limestones. Where these flowerlike animals were abundant on the sea bottom, they must have presented an appearance not unlike that of a field of lilies. Not only did they live in great numbers, but the variety of forms which were developed was large.

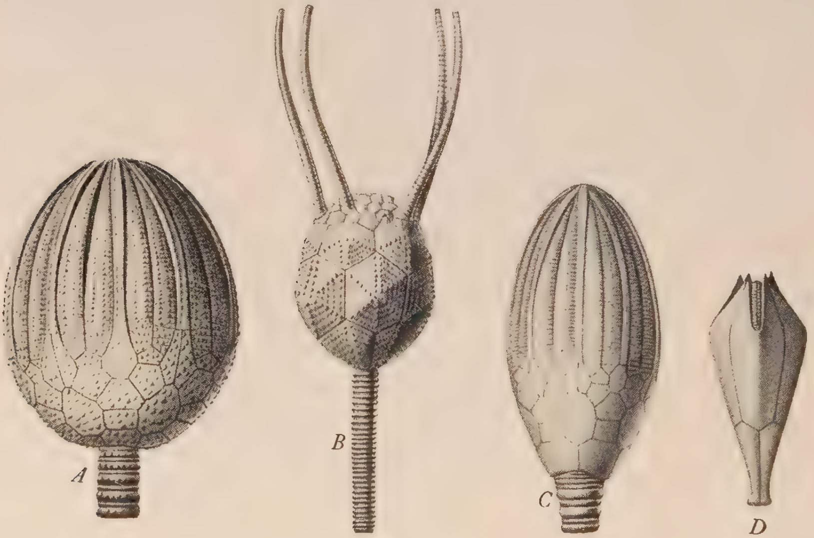


FIG. 415. — Silurian crinoids: *A, Eucalyptocrinus elrodi; C, Eucalyptocrinus crassus* (closed). Cystoid: *B, Caryocrinus ornatus*. Blastoid: *D, Troostocrinus reinwardti.*

Cystoids (Fig. 415 *B*) continued to be abundant when conditions were favorable for their growth, but at the close of the period they were no longer an important element of the fauna.

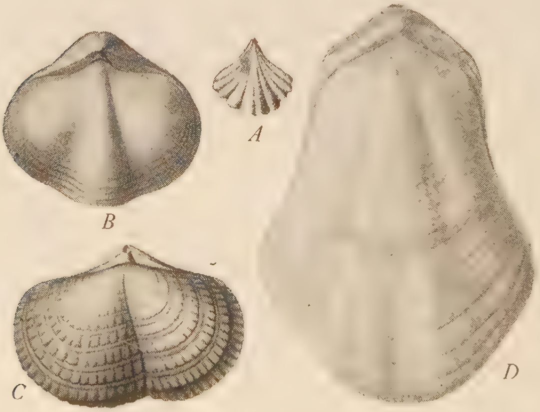


FIG. 416. — Silurian brachiopods: *A, Rhynchotreta cuneata americana; B, Spirifer radiatus; C, Streptis grayi; D, Pentamerus oblongus.*

Molluscoidea

Brachiopods. — Although the Silurian brachiopods (Fig. 416 *A–D*) differed almost entirely from those of the Ordovician in species, the importance of the race did not diminish. Some improvements in structure were accomplished, and new genera which later became important were evolved. The evolutional changes were doubtless directly or indirectly the result of the changes in environment, which consisted in shiftings of the epicontinental seas and the consequent frequent migrations of faunas and struggles between them.

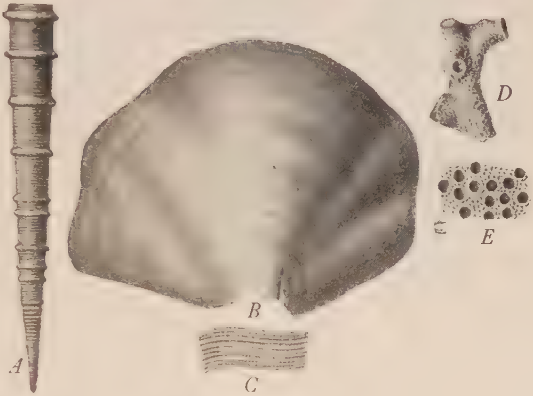


Fig. 417. — Silurian bryozoans (*B–E*), and pteropod (*A*): *A, Tentaculites gyracanthus; B, Lichenalia concentrica; C,* a portion of *B* enlarged; *D, Hallopora elegantula; E,* a portion of *D* enlarged.

Bryozoa. — The coral-like bryozoans (Fig. 417) were less important reef builders in the Silurian than in the Ordovician.

Mollusca

Gastropods. —Aside from an increase in the number and variety of species with elevated spires and in a somewhat greater abundance,

Fig. 418. — Silurian pelecypod: *A, Pterinea emacerata.* Silurian gastropods: *B* and *C,* two views of *Trematonotus alpheus; D, Strophostylus cyclostomus; E, Platyostoma (Diaphorostoma) niagarense.*

no important changes in the *gastropods* (Figs. 418 *B–E*) are shown.

Pelecypods (Fig. 418 *A*) also continued much as in the Ordovician.

Cephalopods. — Curved and coiled *cephalopods* (Fig. 419 *B*, *C*) were more numerous than straight forms (Fig. 419 *A*), while the latter were smaller and were commonly ornamented by rings and low, transverse ridges. The body chamber of many Silurian cephalopods was constricted (Fig. 419 *B*), the constriction being apparently for the purpose of protecting the soft parts of the animal from enemies. As in the Ordovician, this class was the most powerful of the time.

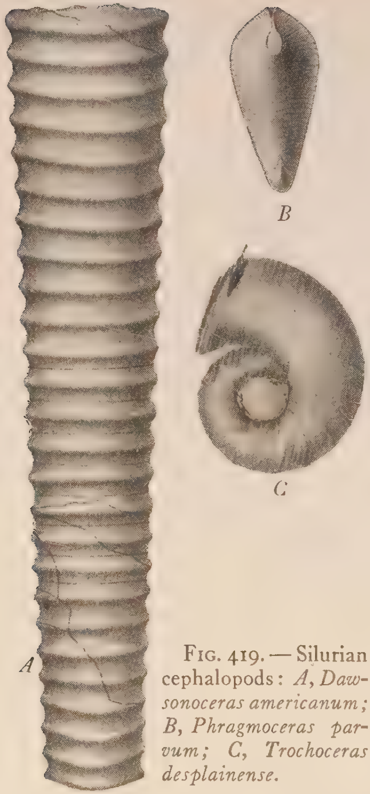


FIG. 419. — Silurian cephalopods: *A*, *Dawsonoceras americanum*; *B*, *Phragmoceras parvum*; *C*, *Trochoceras desplainense*.

Arthropoda

Trilobites. — This interesting class (Fig. 420 *A–D*) was still important, but the decline had already begun and it was numerically decidedly less prominent than in the Ordovician (Fig. 421). Since no new families appeared, the general aspect

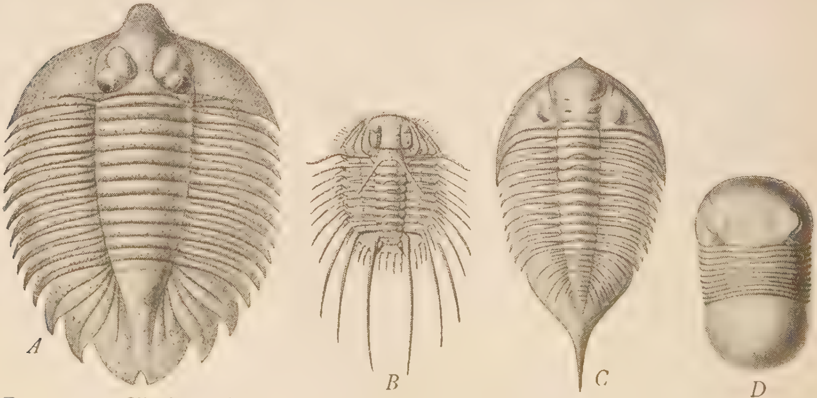


FIG. 420. — Silurian trilobites: *A*, *Arctinurus* (*Lichas*) *boltoni*; *B*, *Ceratocephala dufrenoyi*; *C*, *Dalmanites limulurus*; *D*, *Bumastus* (*Illænus*) *ioxus*.

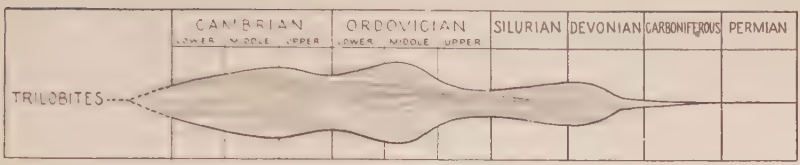


FIG. 421. — Table showing the history of the trilobites. It is seen that the class did not gradually increase and then gradually decrease, but that there were times during which the species and individuals greatly increased and others in which, for a time, there was a decrease. (Modified after Raymond.)

of the class did not differ greatly from that of the preceding period. The most significant change from the Ordovician was in the disappearance of Ordovician genera.

Eurypterids. — The arthropods (Greek, *arthron*, joint, and *pous*, foot), the branch of which the crustaceans and insects are members, reached their greatest size in the eurypterids (Fig. 422). Some of the Silurian forms attained a length of over six feet, while in the Devonian there were giants eight feet long. They, together with the giant cephalopods, were probably the terrors of the sea until the fish obtained the mastery. They had elongated bodies covered with a leathery or horny integument. On the under side were six pairs of legs, of which the first had large or small pincers. Eurypterids are related to the horseshoe crabs (Limulus). The presence of gills and their association with cephalopods and trilobites in the Ordovician show that they lived in water and were for the most part mud crawlers, although some were good swimmers.

FIG. 422. — Silurian eurypterid: *Dolichopterus macrocheirus.* (After J. M. Clarke.)

They were at first marine animals, but late in the Paleozoic became adapted to brackish and possibly to fresh-water conditions, and there is evidence for the belief that some even lived in lagoons where the water was more salty than that of the sea.

Scorpions. — The structure of the Silurian scorpions (Fig. 423) indicates that they were air-breathers. If this interpretation is correct they were the first animals that lived out of water. They appear to have had their origin in the Eurypterids.

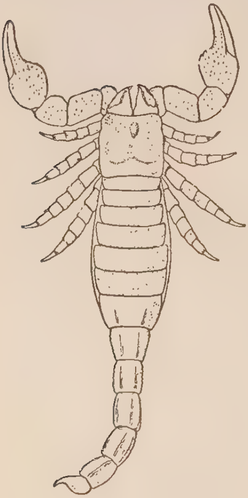


FIG. 423. — Restoration of a Silurian scorpion.

Fishes

Fragmentary fish remains have been found in Silurian rocks (Fig. 424 *A*, *B*) of both Europe and America. The fact that fishes were abundant and of considerable variety in the Devonian is presumptive evidence that a somewhat varied fish fauna existed during the closing days of the Silurian.

SUMMARY

Life on the Land. — It is probable that the lands of the period were clothed with plants, but if so, little evidence is afforded either from the remains of plants or of land animals. The highly developed land plants of the Devonian (p. 467), however, are indirect evidence of the

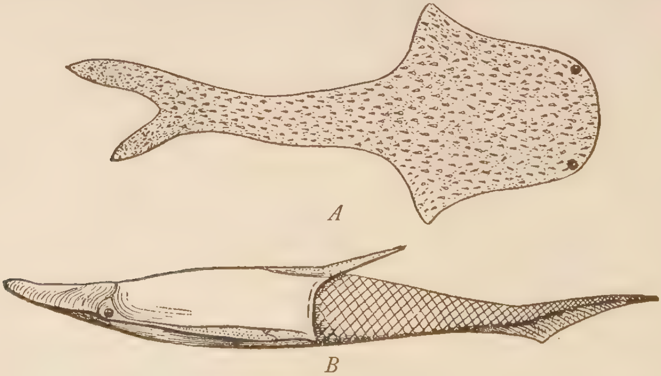


FIG. 424. — Restorations of Silurian fishes (ostracoderms): *A*, *Thelodus*; *B*, *Pteraspis*.

existence of land plants in the preceding period. Nevertheless, the absence of the sediments of fresh-water lakes in America, where land fossils are likely to be preserved, leaves us without evidence, although it does not prove that there were no land plants or animals.

Migration. — The presence of thirty or more identical species in the Silurian strata of Missouri and northwestern Europe indicates that migration between the two continents took place. This presumption is strengthened by the discovery of a peculiar genus of coral (Fig. 413 *E*, p. 444) whose quadrangular opening was protected by a calcareous covering. Since the interior seas of North America had no free communication on the east, it is thought that the migration took place along a belt of shallow water which extended through Canada, Alaska, and perhaps the Arctic region.

Climate and Duration. — The climate of this period seems to have been uniform over the entire world, as during the preceding periods, there being no positive evidence of the existence of climatic zones. The presence of salt and gypsum beds, locally 40 to 80 feet in thickness, in the Silurian strata (Salina) of New York and Ohio is evidence that desert conditions prevailed during a portion of the period, probably over a considerable area.

The Silurian Period was probably not more than one half as long as the Ordovician.

Close of the Silurian. — The change from the Silurian to the Devonian in eastern North America is even less clearly marked than that between the Ordovician and the Silurian, the formations of one often passing into the other without an unconformity. In portions of Great Britain an unconformity separates the two systems, but in other parts of Europe there is no break in the sedimentation. The separation in such cases is based upon the fauna.

REFERENCES FOR THE SILURIAN PERIOD

BLACKWELDER AND BARROWS, — *Elements of Geology*, pp. 349–357.

CHAMBERLIN AND SALISBURY, — *Geology*, Vol. 2, pp. 368–417.

GRABAU AND SHIMER, — *North American Index Fossils*, Vols. 1 and 2.

SCHUCHERT, CHAS., — *Paleogeography of North America:* Bull. Geol. Soc. America, Vol. 20, 1910, pp. 489–491.

SCOTT, W. B., — *An Introduction to Geology*, pp. 578–589.

ULRICH, E. O., — *Revision of the Paleozoic Systems:* Bull. Geol. Soc. America, Vol. 22, 1911.

CHAPTER XVIII

THE DEVONIAN[1] PERIOD

The passage from the Silurian to the Devonian in eastern North America was without any physical break, the transition from one to the other being marked by no great unconformity. In fact, so gradual was the change that much controversy has arisen as to the exact limits of the two systems. Not only was the change in the lithological character and structure of the strata slight, but the life at the close of the Silurian and the beginning of the Devonian was very similar. Wherever the Devonian seas spread over a wider or different area from that of the Silurian the sediments were laid down unconformably on older rocks. Unconformities of this sort occur in Iowa and elsewhere, but they are inconspicuous and are sometimes with difficulty recognized as unconformities, since the underlying rocks are horizontal and their surfaces had not been greatly roughened by erosion. The lack of great relief as shown in these unconformities affords an evident explanation for the fineness of the sediments in the Western Interior in the closing stages of the Silurian, as well as of those of the early days of the Devonian.

Subdivisions of the Devonian. — The subdivisions of this period in New York state are given below, both because it was in this state that they were first studied with care in North America, and also because the system is best developed there.

Catskill and Chemung sandstones
Portage shale and sandstones
Genesee shale
Tully limestone
Hamilton shale
Marcellus shale
Onondaga limestone
Oriskany sandstone
Helderberg limestone

---

[1] The Devonian received its name from the shire of Devon, England, where a great series of strata of this period occur.

Geography. — The close of the Silurian found few epicontinental seas in North America. In the east (Fig. 425) the Appalachian trough, portions of New York, and certain areas in the Maritime Provinces of Canada were covered with seas, and a bay extended from the Gulf of Mexico toward the north along the valley of the Mississippi. In the west an arm of the sea extended from the Pacific across the site of the Sierra Nevada into Utah. The outlines of these seas were not constant but changed from stage to stage. Later in the period (Fig. 426) the seas spread widely over the continent, calling to mind the submergent condition of the Middle Ordovician and Middle Silurian.

In New York state the formations of the first half of the Devonian are for the most part limestones with occasional shales and sandstones, but in the later half of the period shales and sandstones predominate. The shales and sandstones were brought into the sea by streams from the Taconics of Massachusetts, and probably from land areas which existed to the north in Canada. The Devonian strata cover a greater area at the surface in New York than any other rocks, and their combined thickness is more than 4000 feet (Fig. 427). They are much thicker in Pennsylvania, but thinner in the Mississippi Valley, and are said to be 8000 feet thick in portions of Nevada.

FIG. 425. — Map showing the probable outline of North America during a portion of the Lower Devonian. (Modified after Schuchert.)

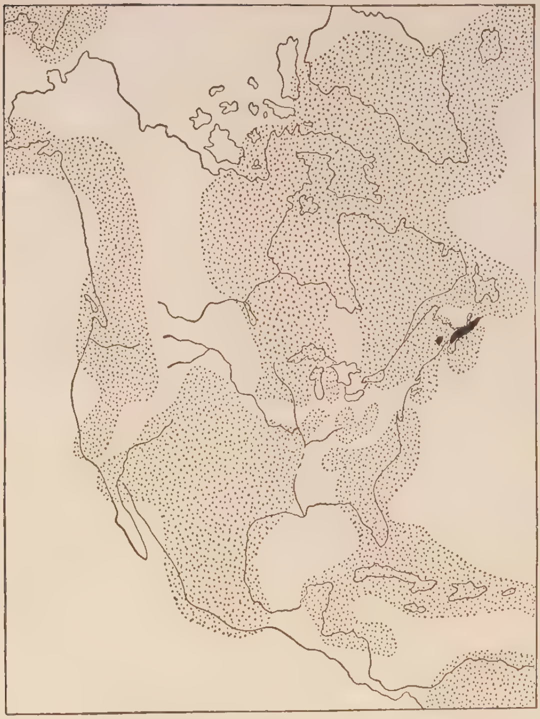


FIG. 426. — Map showing the probable outline of North America during a portion of the Middle Devonian. Solid black shows continental deposits. (Modified after Schuchert.)

The Devonian in New York. — There are three Devonian formations in New York which deserve especial mention: the Oriskany, the Onondaga, and the Catskill. The Oriskany is a sandstone formation made, for the most part, of clean beach sands, which in New York is from a foot to several feet thick and in the Middle Atlantic States is several hundred feet thick. The formation indicates a raising of the land or an increase in the rainfall, or a combination of the two, since stronger currents are necessary to supply coarse waste.

The Onondaga limestone with its wealth of corals and brachiopods indicates warm, clear seas of long duration surrounded by low lands.

The Catskill formation, thousands of feet thick, extends from Virginia to the Catskill Mountains in New York and is a great delta deposit, made of alternate layers of sandstone and shale, sometimes the one and sometimes the other predominating. Upon this assumption the whole constitutes a delta. The form of the plain was probably somewhat similar to that of the high plains region of the western interior of North America (p. 588) (Barrell).[1] While the Catskill delta was being built up, muds were accumulating in the shallow seas (Portage and Chemung).

FIG. 427. — A Section in New York state showing the relation of the Ordovician, Silurian, and Devonian. (After W. J. Miller.)

---

[1] Barrell, J., — *The Upper Devonian Delta of the Appalachian Geosyncline:* Am. Jour. Sci., Vol. 36, 1913, pp. 429–472; and Vol. 37, 1914, pp. 87–109, 225–253.

Continent of Appalachia. — The continent of Appalachia, situated east of the present Appalachian Mountains, which during the preceding periods of the Paleozoic was supplying the streams with sediment for the Appalachian geosyncline, was extensive at this time and was probably a broad, mountainous upland whose eastern boundary may have been beyond the present eastern limit of the continental shelf. This conclusion is justified when the volume of sediments laid down in the Appalachian trough is computed. Such a computation shows that the crest of Appalachia would have had to be lowered from five to seven miles to supply the Upper Devonian sediments, if it had not extended beyond the continental shelf. (Barrell.) It seems likely, therefore, that Appalachia extended from the edge of the Appalachian trough eastward over the present site of the continental shelf and probably fifty miles beyond. The broad Appalachian continent probably never reached Alpine heights, but was rather slowly raised as the Appalachian trough sank. The sediments of the trough are those formed from igneous rocks of the land which had been subjected to chemical decay, and are not such as would have resulted from the mechanical disintegration of frost or changes in temperature. The sediments, moreover, are seldom coarse, showing that the streams did not flow from a high, mountainous region in proximity to the sea.

Igneous Rocks. — In Maine, New Brunswick, and Nova Scotia, granite intrusions and volcanic extrusions took place during the Devonian. The city of Montreal lies at the foot of a volcano, and there are other volcanoes to the southeast. This was the first premonitory indication of the movements which were later to form the great Appalachian Mountains. When North America as a whole is considered, the Devonian Period closed with almost no deformation.

Devonian Oil and Gas. — A discussion of the Devonian would be incomplete without mention of the important oil and gas-bearing strata of West Virginia, Pennsylvania, and southwestern New York. The oil and gas are more likely to be found at or near the crests of low anticlines (p. 425) than in any other situation.

Devonian of Other Continents. — Epicontinental seas were widespread in Europe and Asia during the Devonian, and smaller seas covered portions of Africa, South America, and Australia. The Devonian of England is of unusual interest because of the development of a continental deposit of red sandstone, called the "Old Red Sandstone." It appears to have been laid down under desert conditions, although no gypsum or salt beds prove this contention. In addition to the Old Red Sandstone there are marine deposits containing abundant fossils. Volcanic action in Europe during the Devonian is proved by thick volcanic accumulations in Great Britain and west central Europe.

Life of the Devonian

The invertebrate life of this period was, in general aspect, like that of the Silurian, but there were many changes in genera and an almost total change in species. The contrast between the invertebrate life of the Silurian and the Devonian was about as marked as that between the Ordovician and the Silurian. As in the foregoing periods, certain species were characteristic not only of the period as a whole but of each of its stages.

Cœlenterata

Corals (Fig. 428 *A–C*) were present in great numbers and species, being almost or quite as abundant as in the Silurian. *Cup corals* (Tetracoralla, Fig. 428 *A*, *C*), *honeycomb corals* (Favosites), and *organ-pipe corals* (Syringopora) flourished when conditions were favorable, but *chain corals* (Halysites) had become extinct in the beginning of the period.

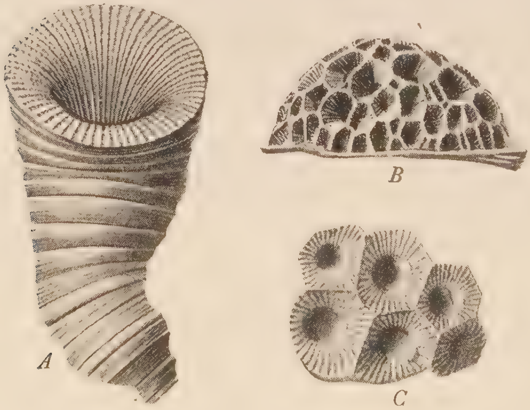


Fig. 428. — Devonian cup and compound corals: *A*, *Heliophyllum halli*; *B*, *Pleurodictyum stylopora*; *C*, *Acervularia davidsoni*.

The coral-reef character of some of the limestones of the period is splendidly exhibited at the falls of the Ohio, Louisville, Kentucky, "where the corals are crowded together in great numbers, some standing as they grew, others lying in fragments, as they were broken and heaped by the waves, branching forms of large and small size mingling with massive kinds of hemispherical and other shapes." "Some of the cup corals are 6 or 7 inches across at the top, indicating a coral animal 7 or 8 inches in diameter." "Hemispherical compound corals occur 5 or 6 feet in diameter." "The various coral polyps of the era had, beyond doubt, bright and varied colorings, like those of the existing tropics, and the reefs were therefore an almost interminable flower garden." (Dana.)

Corals are not equally abundant in all Devonian formations; they are rare in shales and sandstones, but are usually common in limestones. This is not remarkable, since corals do not thrive in muddy waters.

Echinodermata

Crinoids (Fig. 429 *B*) and *starfish* (Fig. 429 *A*) were much more abundant than in previous periods, but *cystoids* were rarer than in the Silurian.

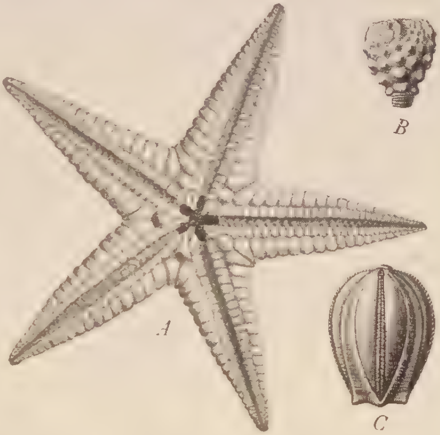


FIG. 429. — Devonian starfish, crinoid, and blastoid: *A, Devonaster eucharis; B, Melocrinus milwaukeensis; C, Nucleocrinus verneuili.*

Blastoids (Greek, *blastos*, bud) were locally abundant. These echinoderms (Fig. 429 *C*), as the name implies, were oval, with five petal-like divisions resembling a flower bud. They were armless and were attached to the sea bottom by a jointed stem. Beginning in the Ordovician, they culminated in the Mississippian (p. 480), after which they occurred sparsely and disappeared with the Paleozoic.

The *starfish* of Devonian times had already acquired the habits of feeding which they possess to-day.[1]

Molluscoidea and Mollusca

Brachiopods (Fig. 430 *A-P*) were never more abundant in individuals and species than during portions of this period, and many characteristic species were present. Long-hinged *spirifers* were especially abundant and highly developed throughout the Devonian.

Bryozoans (Fig. 431 *A–D*) were locally abundant.

Pelecypods (Fig. 432 *A–E*) flourished where the bottoms were muddy and other conditions favorable.

Gastropods (Fig. 433 *A–C*) were subordinate in numbers to the pelecypods but were not uncommon.

---

[1] Clarke, J. M., — *Early Adaptation in the Feeding Habits of Starfish:* Acad. Nat. Sci., Philadelphia, Vol. 15, 1912, pp. 113–118.

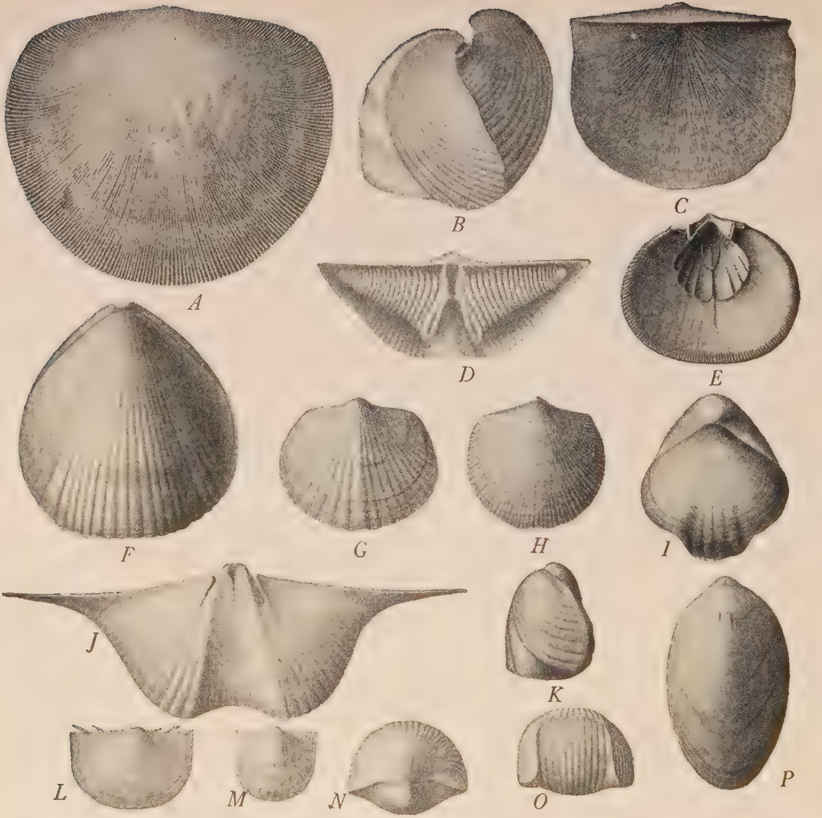


FIG. 430. — Devonian brachiopods: *A, Hipparionyx proximus; B, Spirifer acuminatus; C, Stropheodonta demissa; D, Spirifer mucronatus; E, Rhipidomella oblata; F, Camarotoechia endlichi; G, Tropidoleptus carinatus; H, Atrypa reticularis; I, Gypidula galeata; J, Spirifer disjunctus; K, Eatonia medialis; L, Chonetes coronatus; M, Productella spinulicosta; N* and *O*, two views of *Hypothyris cuboides; P, Rensselæria ovoides.*

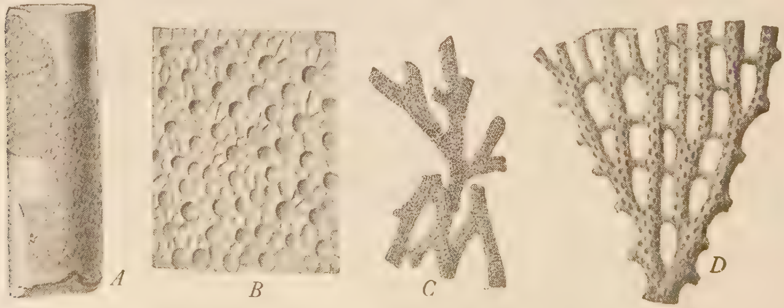


FIG. 431. — Devonian bryozoans: *A, Fistulipora micropora* surrounding a crinoid stem; *B*, a portion of the same greatly enlarged to show the arrangement of the cells; *C*, branches of *Cystodictya hamiltonensis; D, Polypora lilæa.*

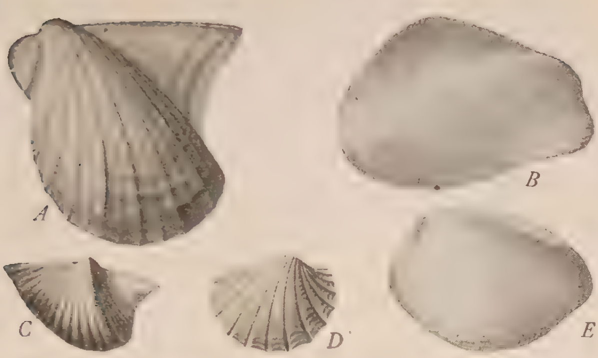


FIG. 432. — Devonian pelecypods: *A, Pterinea flabellum; B, Modiomorpha concentrica; C, Conocardium ohioense; D, Buchiola retrostriata; E, Palæoneilo constricta.*

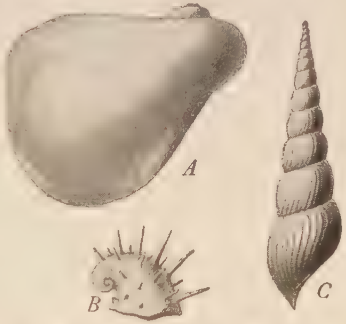


FIG. 433. — Devonian gastropods: *A, Strophostylus expansus; B, Platyceras dumosum; C, Loxonema noe.*

Cephalopods. — A rather inconspicuous member of this class, the goniatite (Greek, *gonia*, angle), but one whose modified descendants were to become the most prominent invertebrates of the Mesozoic, began in the Devonian. The important characteristic of this coiled cephalopod was the angled and lobed suture line (Fig. 434 *A*, *B*), *i.e.*, instead of smooth partitions (septa, p. 434) which joined the outer shell in straight lines or in simple curves, the septa were crumpled at the edges at the juncture with the outer shell, forming *angled*

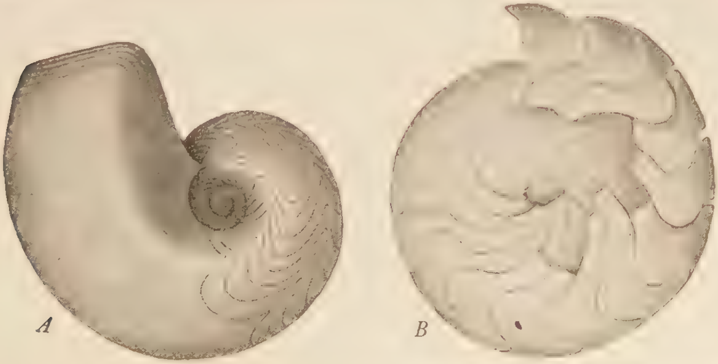


FIG. 434. — Devonian cephalopods: *A, Manticoceras oxy; B, Tornoceras mithrau.*

sutures. The straight (Orthoceras) and coiled (Gomphoceras) cephalopods with simple sutures continued throughout the period but were much less common in the later portion.

Arthropoda

Trilobites. — During the earlier stages of the Devonian more than 50 species of *trilobites* (Fig. 435 *A–C*) are known to have existed, but the numbers rapidly decreased during the later stages. In the earlier portions of the period especially, a number of highly ornamented, spinous forms (Fig. 435 *A*) lived, but later these extravagant species largely disappeared, and those of simpler outlines remained. The decline of the trilobites during the Devonian was very marked, and at its close they were on the verge of extinction, although a few survived until the close of the Paleozoic. Other crustaceans (Fig. 436) also lived in considerable abundance.

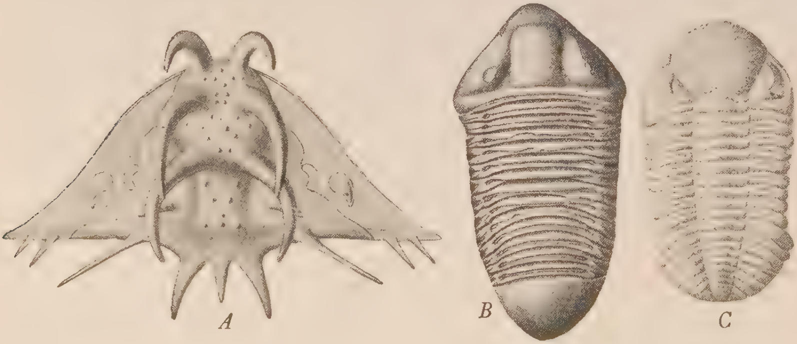


Fig. 435. — Devonian trilobites: *A, Lichas (Gaspelichas) forillonia* (cephalon); *B, Dipleura dekayi; C, Phacops rana.*

Fig. 436. — *Echinocaris punctata*, a Devonian crustacean.

Barnacles, which are retrograde crustaceans that have given up a free-moving existence for a stationary one in which they are protected by a calcareous covering, began in the Ordovician, but the common acorn barnacle began in this period.

Eurypterids attained their greatest size during the Devonian, one species reaching a length of almost eight feet (Fig. 437).

Insects. — No undoubted remains of insects have been found in strata of this or earlier periods, although their discovery may be expected at any time.

Fishes

FIG. 437. — *Stylonurus*, a gigantic Devonian eurypterid, some of which were eight feet long. (After Clarke and Ruedemann.)

The appropriateness of the term Age of Fishes as applied to the Devonian Period is evident when the importance of this great class, not only in the life of that time but as the probable progenitors of all subsequent vertebrate life, is considered. Fish were the rulers of the Devonian seas and rivers, perhaps even to a greater degree than were the trilobites in the Cambrian and the cephalopods in the Ordovician. The fact that fish were abundant during the period does not imply that other forms of life were less abundant than in previous periods. For example, brachiopods are exceedingly common fossils in almost all Devonian strata, while in most of the rocks of this age fish fossils are extremely rare and a search of many days may not be rewarded by even a fragment.

Ostracoderms. — One of the strangest classes of Devonian animals was the ostracoderm (Greek, *ostrakon*, shell, and *derma*, skin). These were fishlike in shape but were probably not even closely related to fishes. The description of one well-known member of the class (Cephalaspis, Greek, *cephale*, head, and *aspis*, shield) gives a general notion of this group (Fig. 438 *A*). The most striking feature was the crescent-shaped plate which covered the head and fore part of the body. Besides the protection afforded by this head shield, the tail was covered with rhomboidal scales. The eyes were situated close together on the top of the head. The lower jaw, if it ever existed, has not been found. Although many hundreds of the bony parts have been found, no internal skeleton has been discovered, and it is therefore probable either that none existed or that it was cartilaginous and was consequently incapable of fossilization. In another genus (Bothriolepis) a pair of appendages encased in bony plates, somewhat as are the appendages of a lobster, extended from the sides of the head. Ostracoderms seldom attained a size greater than 6 or 7 inches.

Certain inferences as to the habits of ostracoderms can be drawn from their structure. They probably lived on the sea bottom as did the trilobites, either burrowing in the mud above which only their eyes and their dorsal shield showed, or because of their dull coloring crawling over it inconspicuously. The fact that they were protected implies that they had to contend with enemies more powerful than themselves. They lived in large numbers in certain localities, as is shown by the great abundance of their shields which form thin beds in some places and are said to be hardened by the oil from their remains.

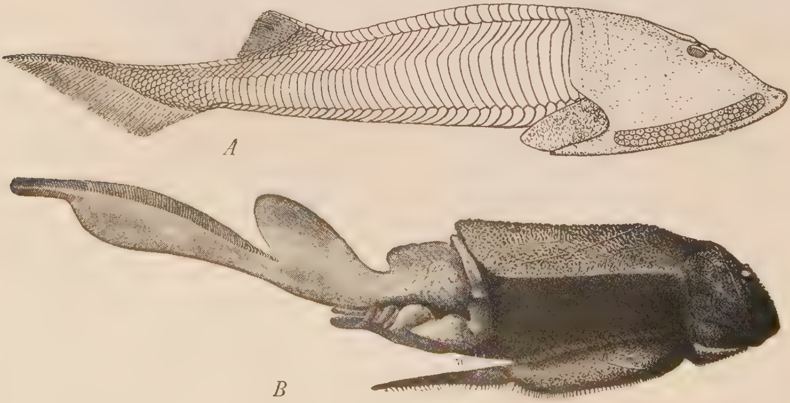


FIG. 438. — Devonian ostracoderms: *A*, *Cephalaspis*, about six inches long; *B*, *Bothriolepis*, about seven inches long.

Ostracoderms began in the Ordovician, reached their climax in the Devonian, and became extinct at its close.

Sharks. — Sharks lived in the Devonian in considerable numbers, but since their skeletons were cartilagenous the fossil evidence of their existence consists largely of teeth, spines (which probably stood in front of the dorsal fin), and small bony denticles which were doubtless embedded in the skin. The best known and most simple in structure of these ancient sharks (Cladoselache, Fig. 439 *A*) varied from two to six feet in length. It had a short, blunt snout with the mouth situated on the lower side but farther front than in the modern shark.

The teeth occurred in clusters (Fig. 440) and were arranged in six or seven rows one behind the other. The fins were very simple, consisting of a flap of skin strengthened by straight rods of cartilage. It was very unlike modern sharks in the contour of its body.

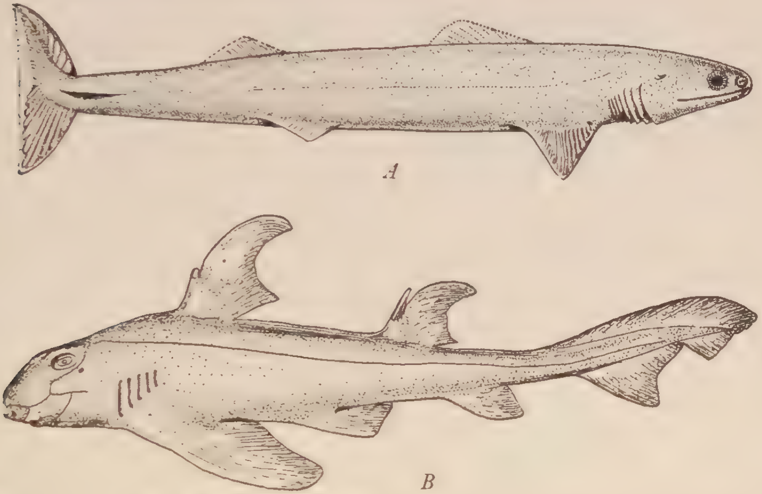


Fig. 439. — *A*, shark, *Cladoselache*, which sometimes reached a length of six feet (see Fig. 440); *B*, the Port Jackson shark, *Cestracion*, a modern shark of ancient type.

Other sharks, now represented by the Port Jackson shark of Australian waters (Cestracion, Fig. 439 *B*), were abundant in the later Paleozoic, judging from the number of their spines and pavement teeth. The teeth of these sharks have been called "cobblestone" pavement teeth because of their resemblance in shape and arrangement in the jaw to a pavement. Such teeth would be of use in crushing thin-shelled crustaceans and shellfish, but could not have been used for rending. It is evident, therefore, that their possessors probably lived on muddy bottoms and fed on brachiopods, pelecypods, or crustaceans. The structure of the tooth plate of sharks "is very much like that of a shark's skin, and it is the teeth of these and other sharks that best illustrate the fact that teeth are really modifications of the skin and do not belong in the same category as bones."

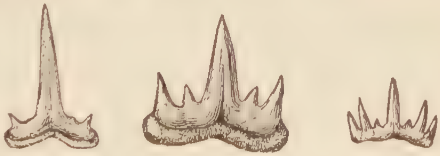


Fig. 440. — Teeth of *Cladoselache*.

Lungfish.[1] — (1) *Armored Lungfish.* — The most formidable and remarkable fish of the Devonian, as far as appearance and size is concerned, were related to the rare lungfish of to-day, although they probably did not possess lungs. One of the most remarkable of the Devonian lungfish was the Dinichthys (Greek, *deinos*, terrible, and *ichthus*, a fish) (Fig. 441*A*) which grew, in one species, to be 25 feet long, and resembled an overgrown catfish, in external form. The head, which in one species was six feet broad, and the front of the body were protected by thick bony plates, although the posterior portions seem to have been quite naked unless covered by a leather-like skin, as is perhaps indicated by certain marks upon the exterior of the bony plates. Their powerful jaws were adapted for tearing and cutting, and their shape formerly led to the belief that these fish were fierce,

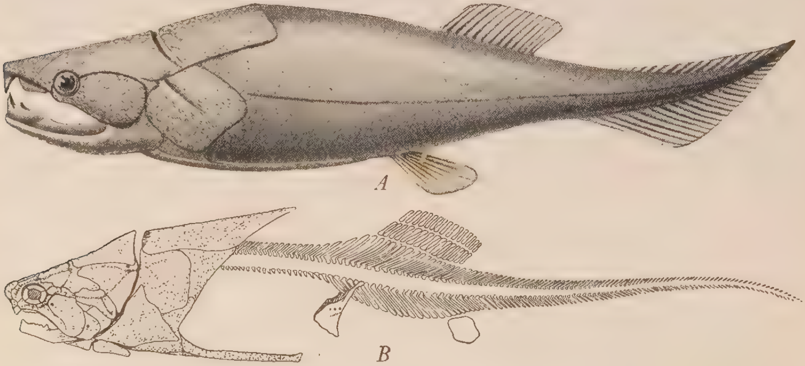


FIG. 441. — Armored lungfishes: *A*, *Dinichthys*, the giant fish of the Devonian, some of which attained a total length of more than ten feet, with head three feet long; *B*, *Coccosteus*, a fish of much smaller size.

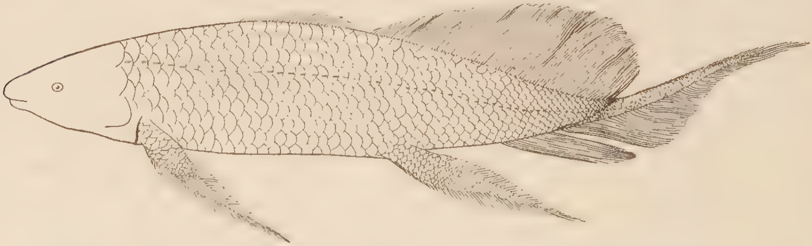


FIG. 442. — An unarmored lungfish, *Scaumenacia*.

---

[1] There is much doubt as to the relationship of the armored lungfish, some holding that they should be placed with the higher ostracophores (Bothriolepis, etc., in the group Placodermata), retaining for the rest of the ostracoderms (Cephalaspis) the name Enostracophori.

predaceous creatures, but it is more probable that they lived on the ocean bottom and subsisted largely on shellfish, using their powerful jaws for crushing. With their heavy armor and clumsy shape they were probably sluggish in their movements.

(2) *Unarmored Lungfish.* — Another abundant group of lungfishes whose descendants have succeeded in living to the present were unhampered by armor but were covered with thin scales (Fig. 442). A modern representative (Ceratodus) lives in Australian waters, and two other genera are known, one in Egypt and one in South America.

Ganoids. — (1) *Fringed-finned Ganoids* (*Crossopterygians*). — Evolutionally, this is the most important of the Devonian fishes, since it possessed so many characters in common with early amphibians (p. 485) that it is probable that the latter arose from this order. The fringe-finned ganoids had *conical teeth generally fluted*, were covered with scales which were rhomboidal in some species and rounded in others, and had *limblike fins* (Fig. 443) which were jointed to the skeleton within the body.

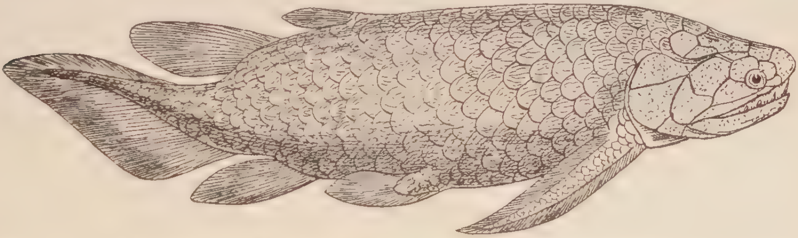


FIG. 443. — A fringe-finned ganoid, *Holoptychius*. Some of these were four feet long.

(2) Another order of ganoids (Actinopteri) may, for convenience, be called *typical ganoids* to distinguish them from the fringe-finned ganoids. These fishes, for the most part, had thick, rhomboidal scales, such as those of their modern representative, the gar pike

FIG. 444. — A typical ganoid, the modern gar pike.

(Fig. 444). Typical ganoids were the most abundant and characteristic fish of the Triassic and Jurassic.

Teleosts or Bony Fish. — The typical fish of to-day, such as the trout, perch, cod, and mackerel, were absent and do not appear until the Mesozoic.

Comparison of Devonian and Modern Fish. — The teeth of Devonian and Carboniferous fishes were adapted for crushing and few had the sharp, rending teeth possessed by fish to-day. The fishes of the Devonian and Carboniferous were, as a class, massive and clumsy as compared with those of the present, and their bodies were probably less flexible. In Devonian fishes the backbone runs through to the end of the tail, and the fin is formed by vertical rays extending from above and below (Fig. 445 *D*). In some, the resulting fin is symmetrical, but in others, as in the modern shark, it is unsymmetrical, the backbone turning upwards with an unequal lobe formed of rays on the under side. The tails of all Devonian fishes were either symmetrical or unsymmetrical (Fig. 445 *B*, *D*), but none had the homocercal tail (Fig. 445 *E*) of modern bony fish (Teleosts), in which the backbone ends in a broad plate from which diverging rays spread to form a symmetrical tail of a type very different from that of Devonian fish.

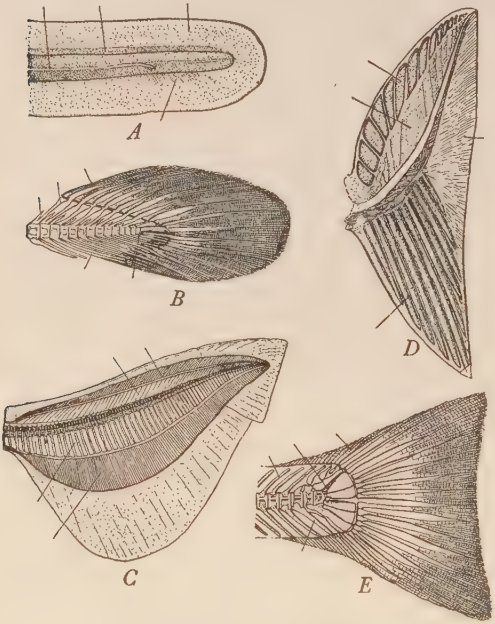


FIG. 445. — Evolution of the tail fin of fishes. (After Dean.) *A*, embryonic tail fin; *C*, uneven-lobed tail fin of the Port Jackson shark; *D*, uneven-lobed tail fin of a Devonian shark, *Cladoselache*; *B*, even-lobed tail fin of the fringe-finned ganoid; and *E*, the tail fin of a modern *Teleost*, such as the trout.

It is interesting in this connection to note that the heavily armored fish were the first to become extinct. They were admirably suited for certain conditions, being protected from their enemies by heavy armor, but when the environment and food changed their very weight and size were of disadvantage (p. 550), and they failed to survive.

Why the Vertebrate Type was " Fit." — The reason for the establishment of the vertebrate type of animals and their rapid rise when once they appeared is evident when their structure is considered. An internal skeleton offers an excellent attachment for muscles, and at the same time permits a great flexibility of the body. As flexibility is necessary for rapid movement through the water, such animals as possessed it were better able both to escape their enemies and to secure their prey. Moreover, it permitted of greater size than as a whole appears to have been possible in other classes. The position and arrangement of the nervous system appears also to have been especially advantageous.

Plants

In the Devonian, for the first time in the history of the world, land plants are known to have been abundant. Discoveries of Silurian ferns and club mosses have been announced, but they are still open to doubt. The plants of the Devonian were of about the same general level of organization as some of those of the present day, although very different in appearance; changes have occurred, as will be pointed out from time to time, but the plants of this early period were, nevertheless, so highly developed as to prove an enormous antiquity. " There are probably no biologists now living who oppose the doctrine of evolution *in toto*, but if there were, they might draw a telling, though fallacious argument from the high organization of the Devonian flora." [1] (Scott.)

At this time horsetails, ferns, club mosses, gymnosperms (of which the cypress, yew, and pines are members), and the extinct sphenophylls and seed ferns (pteridosperms) are known to have existed. The discussion of the Devonian flora will be taken up in the description of the Carboniferous (p. 491), since in this later period it reached the climax of its development.

SUMMARY

Migration and Evolution. — The faunas of the various stages of the Devonian often differ so widely from one another as to suggest

---

[1] By the term *flora* is meant all the plants that grow in a given region or belong to a given period.

that at certain times evolution proceeded at an unusually rapid rate. The difference in the faunas of succeeding stages is due to several causes. At the beginning of the period there were a number of embayments so isolated that the evolution of the faunas of each proceeded independently, until each possessed many characteristic and peculiar species. As the seas spread over the land later in the period these embayments were, one after another, joined together, and as quickly as a waterway opened species from each embayment spread to the others, and a struggle for existence resulted which produced rapid and marked changes in the life, exterminating many species. The conflict thus brought about also caused the rapid rise of new forms not found in any of the original faunas.

The changes in the physical conditions were another cause of rapid evolution. As a result of the extension of the epicontinental seas, new food was doubtless introduced and currents were developed which may have brought about changes in temperature.

It should not be forgotten in this connection, however, that the differences in the faunas of beds of nearly the same age may be due entirely to the fact that one bed was deposited, for example, in shallow water and consequently had a shallow water fauna, and another in deep water and had a deep water fauna. The life of two such beds may, consequently, differ more widely than those of very different ages which were deposited under similar conditions.

Climate and Duration. — Little more can be said of the climate of the Devonian than of the Cambrian and Ordovician, and the evidence, as in the latter, points to a uniformly warm climate over the entire world. In certain places deserts existed as now, while in others extensive swamps were present.

The period was probably little more than half as long as the Ordovician.

REFERENCES FOR THE DEVONIAN PERIOD

Blackwelder and Barrows, — *Elements of Geology*, pp. 358–368.

Chamberlin and Salisbury, — *Geology*, Vol. 2, pp. 418–495.

Grabau and Shimer, — *North American Index Fossils*, Vols. 1 and 2.

Grabau, A. W., — *Early Paleozoic Delta Deposits of North America:* Bull. Geol. Soc. America, Vol. 24, No. 3.

Schuchert, Chas., — *Paleogeography of North America:* Bull. Geol. Soc. America, Vol. 20, 1910, pp. 491–493.

Scott, W. B., — *An Introduction to Geology*, pp. 590–608.

Ulrich, E. O., — *Revision of the Paleozoic Systems:* Bull. Geol. Soc. America, Vol. 22, 1911.

CHAPTER XIX

THE CARBONIFEROUS PERIODS

THE Carboniferous formerly included the Lower Carboniferous (Mississippian), the Upper Carboniferous (Pennsylvanian), and the Permian.[1] American geologists have been led to the conclusion that each of these three subdivisions is of a rank equal to that of the Ordovician, Silurian, or Devonian, and should be called a period. In this study it seems advisable to discuss the life of the three periods together (the Lower and Upper Carboniferous, and Permian) since by so doing the sequence of life changes can best be followed.

MISSISSIPPIAN OR LOWER CARBONIFEROUS

The epicontinental seas (Fig. 446) of the early portion of this period were about as extensive as in the Devonian and occupied much the same regions. As a result, over large areas the transition between the Devonian and Mississippian is not indicated by abrupt changes. Towards the close of the period (Fig. 447), the seas again became constricted.

The sediments brought into the Appalachian trough from the continent of Appalachia were for the most part coarse sands and muds. Sun cracks, ripple marks, the footprints of amphibians, and other evidences indicate an arid or semi-arid climate, and that the sediments (Pocono and Mauch Chunk)[2] were portions of a great delta or alluvial plain built by shifting streams which flowed over it. The Mississippian conglomerates are important mountain makers in the Appalachians.

In the central and western states the Mississippian sediments are

---

[1] The term *Carboniferous* was given because of the large quantities of coal *(carbon)* in the rocks of the period. The subdivisions — Mississippian and Pennsylvanian — were named because of the great development of the rocks of the periods in the Mississippi Valley and in Pennsylvania respectively. The term *Permian* was given because of the wide extent in the province of Perm in Russia.

[2] Barrell, J., — *Origin and Significance of the Mauch Chunk Shale*, Bull. Geol. Surv., Vol. 18, 1907, pp. 449–476.

finer than in the East, and limestone becomes increasingly abundant until, west of Ohio, it constitutes the greater mass of the sediments.

The presence of gypsum and salt in portions of the strata of this age in Michigan shows that the climate, for a time at least, was dry, and that the sea or seas of this region were isolated. The Mississippian gypsum of Nova Scotia implies a similar condition for that region, and, as has been seen, an arid or semiarid climate was present over the lands contiguous to the Appalachian trough.

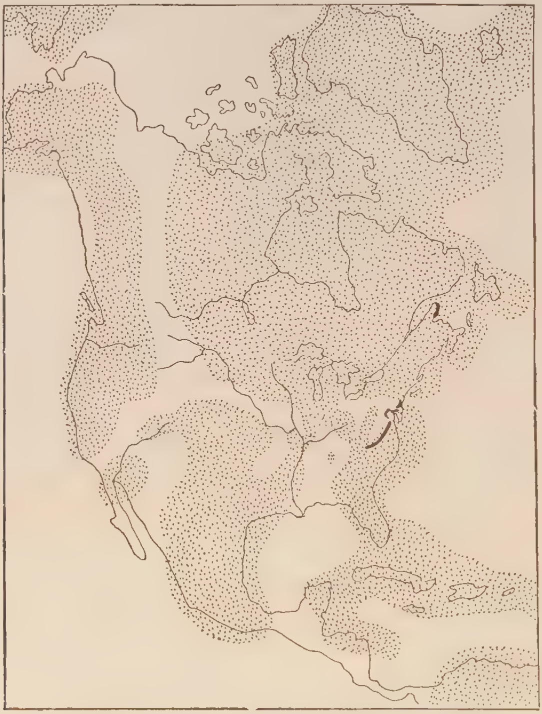


Fig. 446. — Map showing the probable outline of North America during a portion of the Lower Mississippian. Continental deposits are shown in solid black. (Modified after Schuchert.)

The Mississippian seas spread over a large area of the Cordilleras of the West, from Mexico to the Arctic, the strata of this period being several thousand feet thick in certain places.

Close of the Mississippian. — The extensive seas of the early Mississippian were gradually drained, so that before the close of the period the eastern portion of North America was land. In the west the seas also seem to have been withdrawn.

Other Continents. — Mississippian seas spread over a large area in England, Ireland, and Europe, and the sediments which had been accumulating in them were locally folded at the close of the period. The term Paleozoic Alps which has been applied to this folded region assumes that the present folded areas are the "roots of former mountain ranges." Whether erosion kept pace with elevation or not cannot be stated. Strata which are believed to be of this age occur in northern and southern Africa, in western and central Asia and China, in Australia and New Zealand, and in Argentina and Chile. Coal occurs in the strata of this age in China, Russia, England, and elsewhere.

Fig. 447. — Map showing the probable outline of North America during a portion of the Upper Mississippian. The areas in black show where continental deposits were laid down. (Modified after Schuchert.)

Pennsylvanian or Upper Carboniferous

The Pennsylvanian system is generally separated from the Mississippian by an unconformity, the Mississippian strata in some parts of the central United States having been gently folded, faulted, and eroded before the deposition of the Pennsylvanian sediments. A few seas persisted in Utah and Arizona in which sedimentation continued throughout the period without interruption, but such areas are rare. During the emergent condition of the continent the surface rocks were weathered, leaving a residual layer of insoluble quartz and clay. In the east this easily removable material was carried into a long, narrow sea, formed by the down-warping of the eastern part of the old Appalachian trough, where it was worked over and sorted by the seas to form the conglomerate (Pottsville) of the basal Pennsylvanian. As this trough was weighted down by the sediments carried into it by streams, it sank intermittently. For long intervals this area was slightly above the sea level, and the sediments which then accumulated were continental and not marine; at other times the sea encroached on the land and formed immense, shallow seas which, upon being further shallowed by sediment from the land, formed vast, fresh, and

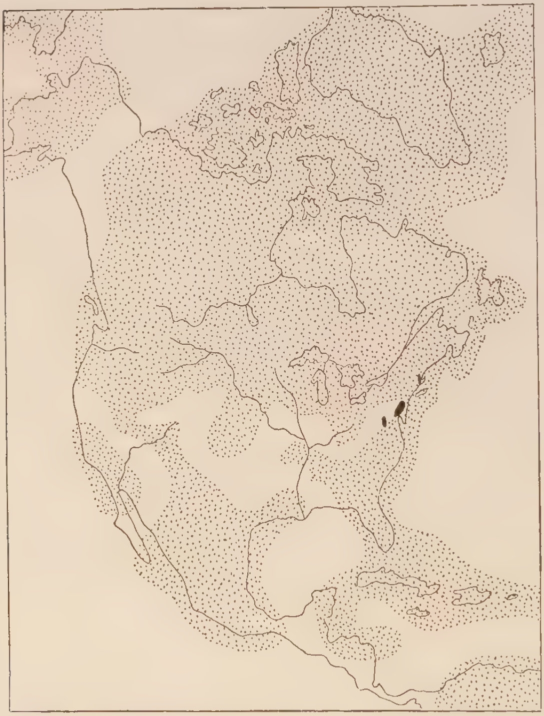


Fig. 448. — Map showing the probable outline of North America during a portion of the Upper Pennsylvanian. Continental deposits are shown in solid black. (Modified after Schuchert.)

brackish water swamps in which were accumulated the great coal beds of the Carboniferous. When the sinking kept pace with the accumulation of the vegetable matter, for many years, deposits of peat 100 or more feet in thickness were sometimes accumulated. These when compressed to coal formed workable coal beds. The accumulation of coal began in the Lower Pennsylvanian (Pottsville), but it was in the upper half of the period that its formation took place on a large scale.

While coal was accumulating in large quantities (never perhaps more than per two cent. of the total thickness of the deposit (Fig. 449) in any one place) in Pennsylvania, West Virginia, Ohio, Tennessee, Illinois, and Iowa, marine conditions prevailed in the west and southwest, and limestones and shales were deposited with no coal. The red Pennsylvanian sandstone of South Dakota and the red conglomerate of Colorado were probably deposited on land by streams in an arid climate. Marine sediments to a depth of several thousand feet were deposited over the site of the Sierra Nevada Mountains.

The thickness of the Pennsylvanian system varies from 4000 to 5000 feet in the Appalachians, to 1000 feet in Kansas and Nebraska. In Texas it is said to be 5000 feet thick and in Nevada about 10,000 feet thick. The probable distribution of the seas and swamps of portions of the Pennsylvanian is shown in the accompanying map (Fig. 448).

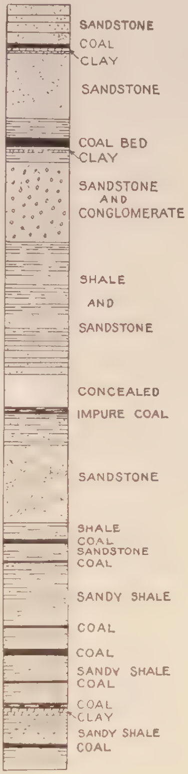


Fig. 449. — Section of coal-bearing strata in Pennsylvania, showing the relative amount of coal and barren rock in a rich field.

Coal Fields of North America

Productive Coal Fields. — (1) *Eastern Canadian and New England Fields.* — Important coal deposits occur in Nova Scotia and New Brunswick on both sides of the Bay of Fundy. Metamorphic coal is also found in Rhode Island, but it is so graphitic as to be of little value at present.

(2) *Appalachian Field.* — The great coal field (Fig. 450) of the world is that which underlies an area of about 50,000 square miles in central and western Pennsylvania, western Maryland and Virginia, West Virginia, and eastern Ohio, Kentucky, and Tennessee. In this should be included the anthracite field, confined to an area of 484 square miles in eastern Pennsylvania.

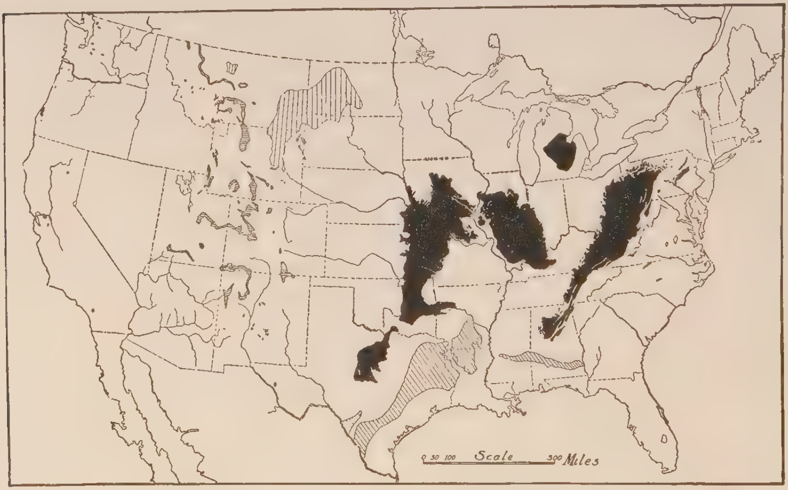


Fig. 450. — Map showing the distribution and extent of the Carboniferous coal fields (black), and more recent coal fields (lines).

(3) *Michigan Coal Field.* — This field covers an area of only 11,000 square miles and was probably formed in an isolated basin. It is not of great value as compared with the Appalachian field, since it is deeply buried and the coal beds are usually comparatively thin.

(4) *The Indiana-Illinois Field* covers an area of about 58,000 square miles, of which 30,000 square miles are underlain by workable coal.

(5) *The Iowa-Missouri-Texas Field* extends from northern Iowa to central Texas and covers an area of about 94,000 square miles, being about 800 miles from north to south. The Indiana-Illinois and Iowa-Texas fields were probably once continuous, but are now separated by the Mississippi Valley.

The Pennsylvanian strata dip beneath much younger strata when traced westward. In the mountains of the Great Basin region, they are found to consist of marine deposits and contain no coal. The coal fields of Wyoming and Colorado are of a later date.

SUMMARY OF THE PENNSYLVANIAN

Iron and Oil. — Beds of iron ore occur associated with coal. Such beds are sometimes continuous, but the ore is often in the form of nodules. The origin of these beds of iron ore is probably the same as that of the " bog iron ore " which is accumulating in the swamps and lakes of the present. Surface waters containing carbon dioxide dissolved iron from the soil and rocks; the dissolved mineral was then carried to swamps and lakes by the streams, and there precipitated, either as iron carbonate or iron hydroxide.

Oil and gas occur in some of the sandstones of the Pennsylvanian system in Illinois, Kansas, Oklahoma, and northern Texas.

Duration. — The exact length of the Pennsylvanian Period is as doubtful as that of the preceding periods, but is usually stated as being about 2,000,000 years. In estimating the duration of former periods it has been necessary to depend upon the rate of sedimentation, but in the Pennsylvanian an additional basis is afforded by the coal. This measure is, however, inaccurate, since the rate of accumulation is not definitely known. The aggregate thickness of the coal in a single section of the Carboniferous is often 150 feet, and sections are known where the total thickness of the coal beds is 250 feet. If the vigorous vegetation of a fertile region in North America to-day were accumulated for 1000 years without loss and compressed to the density of coal, it would form a layer only seven inches thick, but since in the making of coal it is probable that four fifths of the vegetation disappears as carbon dioxide (CO_2), methane (CH_4), and other gases, the rate of accumulation would be only one and one half inches in 1000 years. It is readily seen, therefore, that 1,000,000 or 2,000,000 years may have been required for the accumulation of the Pennsylvanian coal.

Other Continents. — The Pennsylvanian was the greatest coal-producing period of the world. Workable beds occur in Great Britain and Ireland and in all of the principal countries of Europe except Norway, Sweden, Denmark, and Italy. The Pennsylvanian strata in China, Asia Minor, and eastern Siberia contain coal beds, many of which are of great value; in China, especially, coal beds of great thickness and excellent quality have been reported. The Carboniferous strata of Africa, Australia, and South America are seldom coal bearing, but in some areas valuable deposits occur and much coal is mined.

PERMIAN

In North America the Permian is a continuation of the Pennsylvanian and is a period in which the far-reaching seas of the latter were withdrawn. Where the two systems occur in the same section in North America they are almost always conformable. It is, however, more important as the transition period between the Paleozoic and the Mesozoic. In the eastern United States the comparatively small areas of Permian rocks are separated from the underlying Pennsylvanian on the basis of their plant remains, which are more closely related to European Permian plants than to those of the underlying Pennsylvanian. They consist of about 1000 feet of sandstone, shale, and limestone, and a few beds of coal.

In Nova Scotia, New Brunswick, and Prince Edward Island, strata composed of red shale and sandstone are believed to have been deposited in an inclosed basin during the Permian.

During the early portion of the period a shallow sea extended from the Gulf of Mexico through Texas into Kansas and Nebraska, as is shown by the presence of marine fossils in the rocks. Later in the period the sea withdrew, leaving a great region dotted here and there with salt lakes which left beds of gypsum and salt, upon drying. The aridity of the climate of this area is shown not only by the presence of the salt and gypsum, but by the sun-cracked and ripple-marked red sandstones and soft red shales or " red beds." It was a region not unlike the Great Basin of Utah of to-day. These desert conditions continued into the Triassic, and it is, consequently, difficult and in many cases impossible to determine the dividing line between the two systems. Portions of the Pacific border were covered with seas in which marine life abounded.

Before the close of the period the epicontinental seas had, with one or two exceptions, withdrawn from the continent.

Permian Glaciation. —One of the surprising features of the Permian is the evidence of widespread glaciation during the period. The location of the glaciated areas is also remarkable. They occur on both sides of the equator and within 18 to 21 degrees of it; that is, they extend slightly within the torrid zone. The limits of these ancient glaciers are not definitely known, since the evidence has been largely obliterated, but the proof at hand implies an area greater than that during the " Great Ice Age."

The proof of this ancient glaciation is conclusive and consists of bowlder clay, often containing smoothed and striated bowlders which in places rest upon a striated and polished pavement of older rocks. The glaciated areas were not in the polar regions nor, in many places, at a high altitude, as is shown by the relation of the glacial deposits to strata containing marine fossils. In Australia, for example, the glacial formations are interbedded with marine sediments. Moreover, coal beds occur in the formation.

In particular, the Permian glacial deposits occur in the following countries. In India ancient bowlder clay rests, in places, directly upon a striated, roche-moutonnée surface, and some of the glaciated areas extend nearly to sea level. This is remarkable when taken in connection with the fact that the glaciated area is within the tropics. In South Africa the bowlders of the glacial deposit are often striated and rest on a striated rock pavement. In Australia several bowlder beds point to repeated advances of the ice or to several stages of glaciation. Thin glacial moraines of Lower Permian age resting upon a glaciated surface of Upper Carboniferous rocks have been discovered in Germany, and Permian bowlder beds in England have been interpreted as of glacial origin. Bowlder clay of glacial origin occurs in Permian strata in Brazil and Argentina, and conglomerates near Boston, Massachusetts, believed to be in part of glacial origin, are thought to be either of Pennsylvanian or Permian age.

The exact age of the glacial deposits of India, South Africa, and Australia is somewhat in doubt. They are usually called Permo-Carboniferous and occurred either at the close of the Pennsylvanian or in the Lower Permian. The development of annual rings in Upper Permian trees of certain regions has given rise to the belief in warm summers and cold winters for at least a few thousand years near the close of the period.

Permian Deserts. — Over large areas of the earth's surface deserts existed in the Lower Permian, as the ripple-marked and sun-cracked red sandstones and shale and the interbedded salt and gypsum testify. Central and western Europe, England, and western North America are known to have been so affected.

Igneous Activity. — Numerous volcanoes broke out in England during the period, and the rocks were broken by earthquake shocks, as is shown by earthquake fissures filled with what appears to be Permian sandstone.

Appalachian Deformation. — In the discussion of the geography of the various periods of the Paleozoic, attention has been called repeatedly (1) to the continent of Appalachia, a broad upland, sometimes high and sometimes low, and (2) to the Appalachian trough west of it in which much of its waste was poured. Two points have been emphasized: (1) that the trough or geosyncline sank as it was weighted with sediments, and (2) that, as Appalachia was worn down by the streams, a compensating rise took place. With the exception of comparatively short periods of emergence, sediments were accumulating in the Appalachian trough from the beginning of the Cambrian until the Permian, during which time more than 25,000 feet of sediments were laid down. One of the most important upward movements of the trough occurred near the close of the Ordovician, apparently at about the time the Taconic deformation (p. 422) was taking place. Others occurred in the Silurian and between the Mississippian and Pennsylvanian periods. With these and other minor exceptions the great Appalachian trough was the site of deposition during the long periods of the Paleozoic, and a thickness of more than five miles of sediment accumulated.

Towards the close of the Carboniferous the most striking event in the geological history of eastern North America was consummated. At this time the sediments of the Appalachian trough yielded to the stresses that had long been accumulating and folded into a great mountain system (Fig. 351, p. 361), the axes of the folds extending in a northeast-southwest direction, one range reaching from Nova Scotia to Rhode Island, another from New York to Alabama, and a third in Arkansas forming the Ouachita Mountains.

The probable cause of the yielding of this particular portion of the crust to lateral pressure was the fact that the geosyncline was a zone of weakness " just as the bend in a crooked stick determines the point at which it will break when pressure is applied at the ends." The rocks in all portions of the trough were not equally deformed: those in Pennsylvania and West Virginia have been, for the most part, compressed into gentle folds, while those in the southern Appalachians in Tennessee and elsewhere were broken by so many thrust faults that the reconstruction of the region is often difficult. The intensity of the folding diminished from east to west. In eastern Pennsylvania, for example, the folds are more compressed and faults are more common than in the central part of the state, while in the western portion the rocks were little disturbed and are almost horizontal. The greater deformation on the eastern side of the trough is also seen in the character of the coal in eastern and western Pennsylvania.

In the former, it is metamorphosed to anthracite, while in the latter it is bituminous. The effect of lateral pressure on competent strata (p. 257), such as quartzites and limestones, and on incompetent, such as shales, is well shown. Where the former were thick the strata were either thrown into great folds or when broken were thrust over the adjacent rocks. The effect on shales is in marked contrast, for they were crumpled into minute folds and crushed.

Not only were the sediments of the Appalachian trough folded, but the rocks of the continent of Appalachia were also deformed as they had indeed been a number of times before. As a result, those portions of this old land which are at present exposed at the surface are extremely complex.

Although the Permian was the period during which the principal folding occurred, some deformation had previously taken place. In the Ordovician folding occurred, and in the Middle Devonian mountains were formed in Maine, New Brunswick, and Nova Scotia. "The Appalachian revolution began in the Middle Devonian, the first mountain bulwarks being thrown upon the eastern side of the Appalachian system and to the north."[1]

Age of the Deformation. — The time at which the Appalachian deformation took place is known from the usual evidence. The youngest rocks which are infolded are Pennsylvanian. Upon the upturned edges of these the Triassic rocks rest unconformably in certain places. Since the Permian strata are absent in eastern Pennsylvania, it is probable that the deformation took place during the latter and that it continued into the Triassic, since the oldest rocks of that period seem to be everywhere lacking.

Other Continents. — The western half of Europe was part of a large continent that extended from Russia far into the Atlantic. In the southern part of this continent lakes and swampy depressions existed in the earlier Permian, in which rank vegetation grew and large and small amphibians and primitive reptiles dwelt. These swampy areas were drained by an elevation in the Upper Permian which converted them into broad plains separated by hills and mountains. The climatic effect of these changes was marked, some portions of the region becoming very humid and others, from which the moist winds were shut off by the mountains, becoming arid. Volcanic activity was prevalent during a portion of the period. The epoch

---

[1] Barrell, J., — *The Upper Devonian Delta of the Appalachian Geosyncline:* Am. Jour. Sci. Vol. 37, 1914, pp. 225–253.

of elevation was followed by one of subsidence and later by disturbances which cut off a great lake, like the Caspian Sea, and salt and gypsum were deposited as it dried up. During the Upper Permian the thickest known salt deposits were accumulated, one of which, near Berlin, has been penetrated 4000 feet.

Permian strata cover large areas in southern Asia, in Australia, in southern Africa, and in South America, the striking features of which are the extensive glacial deposits (p. 505).

INVERTEBRATES OF THE CARBONIFEROUS

Protozoans. — During the Carboniferous, for the first time in the Paleozoic, Foraminifera became abundant and varied. Certain genera built up limestone deposits, occasionally of considerable thickness. One of the most characteristic forms of the Mississippian (Fusulina) was like a grain of wheat in form and size (Fig. 455 *H*, *I*, p. 482).

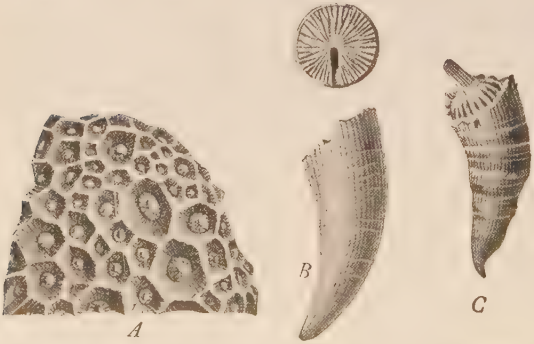


FIG. 451. — Carboniferous corals: *A*, *Lithostrotion canadense* (Mississippian); *B*, *Hapsiphyllum calcariforme* (Mississippian); *C*, *Lophophyllum profundum* (Pennsylvanian).

Cœlenterates and Echinoderms. — *Cup* (Fig. 451 *A*–*C*) and *honeycomb corals* continued to be important in the Carboniferous, and contributed largely to the formation of thick limestone strata. *Blastoids* (Fig. 452 *F*, *G*) were so abundant in the Mississippian that some beds are largely made up of them, but their extinction was reached before the end of the Pennsylvanian. Where favorable conditions existed, *crinoids* (Fig. 452 *A*–*E*) were unusually abundant; especially was this true in the Mississippian. *Sea urchins* (echinoids) were more abundant and larger than ever before, but were subordinate to the crinoids in numbers.

Molluscoids. — Bryozoans lived in considerable numbers. Among many less striking forms was one genus with a peculiar habit of growth about an axis which gave it a screwlike shape, hence the name Archi-

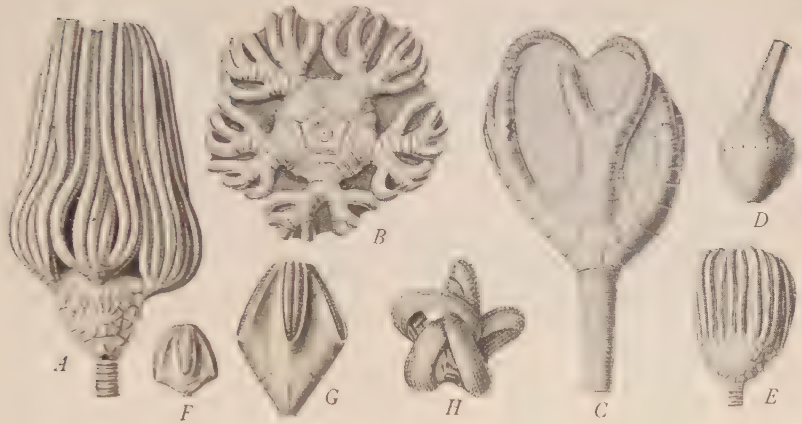


Fig. 452. — Mississippian echinoderms. Crinoids: *A, Actinocrinus multiradiatus; B, Platycrinus discoideus; C, Onychocrinus exsculptus; D, Batocrinus* (*Dizygocrinus*) *rotundus* (with arms removed); *E*, the same as *D* with arms. Blastoids: *F, Pentremites robustus; G, Pentremites pyriformis.* Brittle Stars: *H, Onychaster flexilis.*

medes (Fig. 453). The Carboniferous was rich in *brachiopods* (Fig. 454 *A–M*), but before its close the leading Paleozoic genera had disappeared. One characteristic genus (Productus) (Fig. 454 *A, G*) had one large, convex, spinose valve and one concave one.

Mollusks. — *Gastropods* (Fig. 455 *A–G*) and *pelecypods* (Fig. 456 *A–F*) continued much as in the Devonian. The *cephalopods* (Fig. 457 *A–E*), on the other hand, showed considerable advance in the complexity of the suture lines (p. 530). The angle-sutured goniatites were common, and, before the close of the Permian, ammonites with their complex sutures appeared. Some of the straight, simple orthoceratites continued throughout the Paleozoic into the Triassic.

Arthropods. — *Trilobites* (Fig. 458) and *eurypterids* continued into the Carboniferous, but became extinct at its close.

Insects. — The earliest insects of which any fossils have as yet been found lived in the Carboniferous (Fig. 459 *A, B*), and from that period about 1000 species have been described. They appear to have been more generalized than those

Fig. 453. — Carboniferous bryozoan: *Archimedes wortheni* (Mississippian).

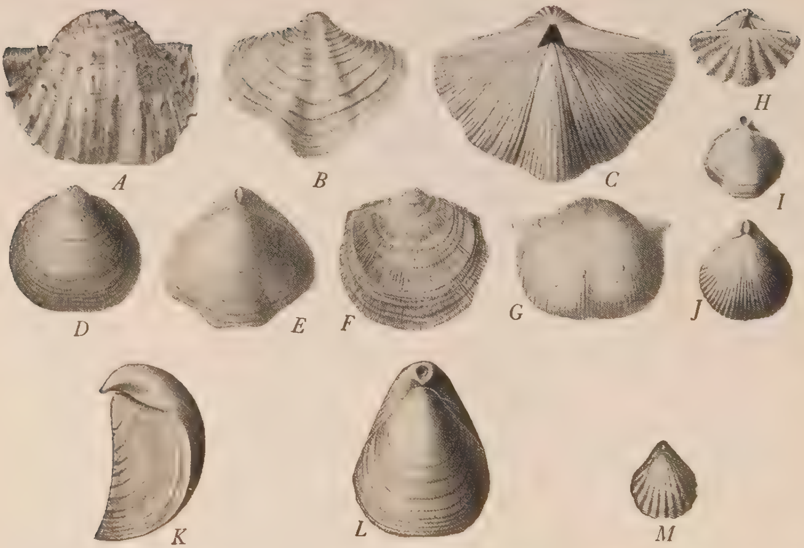


Fig. 454. — Carboniferous brachiopods: *A, Productus costatus* (Pennsylvanian); *B, Athyris lamellosa* (Mississippian); *C, Spirifer cameratus* (Pennsylvanian); *D, Rhipidomella burlingtonensis* (Mississippian); *E, Seminula argentea* (Pennsylvanian); *F, Derbya crassa* (Pennsylvanian); *G, Productus burlingtonensis* (Mississippian); *H, Spiriferina spinosa* (Pennsylvanian); *I, Seminula subquadrata* (Mississippian); *J, Eumetria marcyi* (Mississippian); *K, L, Dielasma bovidens* (Pennsylvanian); *M, Hustedia mormoni* (Pennsylvanian).

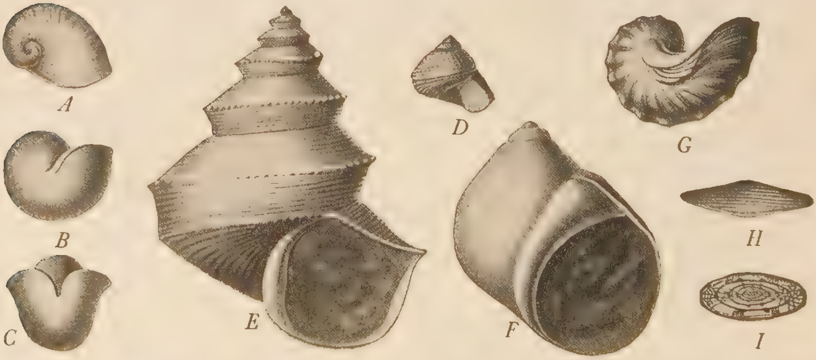


Fig. 455. — Carboniferous gastropods: *A, Platyostoma broadheadi* (Mississippian); *B, C,* two views of *Bellerophon sublævis* (Mississippian); *D, Pleurotomaria nodulostriata* (Mississippian); *E, Worthenia tabulata* (Pennsylvanian); *F, Naticopsis altonensis* (Pennsylvanian); *G, Bellerophon percarinatus* (Pennsylvanian). Foraminifera: *H, Fusulina secalica* (Mississippian); *I,* section of *Fusulina,* showing structure.

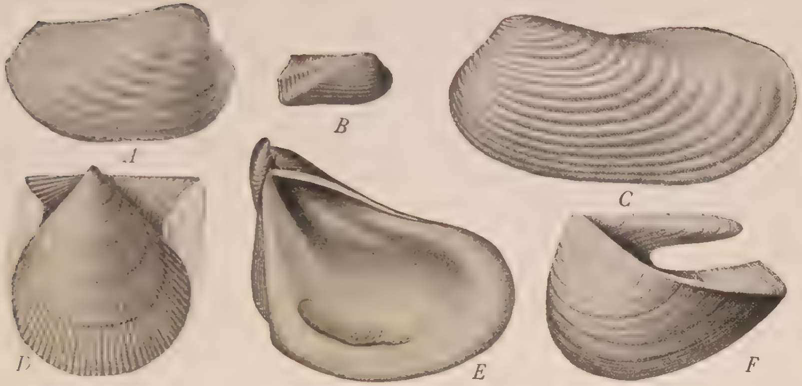


FIG. 456. — Carboniferous pelecypods: *A*, *Grammysia hannibalensis* (Mississippian); *B*, *Pleurophorus tropidophorus* (Pennsylvanian); *C*, *Allorisma terminale* (Pennsylvanian); *D*, *Aviculopecten occidentalis* (Pennsylvanian); *E*, *Myalina recurvirostris* (Pennsylvanian); *F*, *Monopteria longispina* (Pennsylvanian.)

of subsequent periods; that is, they were simple in structure and united characteristic features of two or more distinct groups, and were therefore probably the ancestors of those insects whose characters they combine. One extinct order (*Paleodictyoptera*, old, netted wing) is especially interesting because it is believed to be the stock from which all insects were descended. Carboniferous

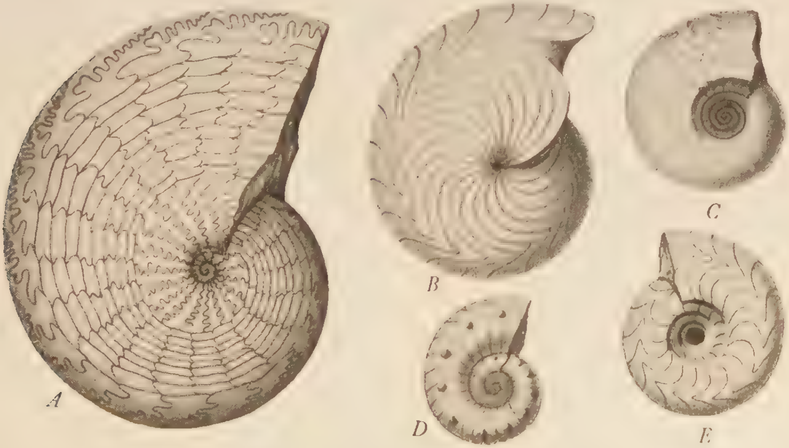


FIG. 457. — Carboniferous cephalopods: *A*, *Medlicottia copei*; *B*, *Aganides rotatorius*; *C*, *Waagenoceras cumminsi*; *D*, *Temnocheilus forbesianus*; *E*, *Muensteroceras oweni*.

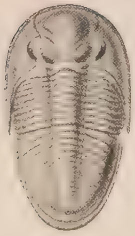


FIG. 458. — Carboniferous trilobite: *Phillipsia major*.

insect groups seem widely different when the external form only is considered, but a more careful study shows that the differentiation had little depth. The wings were all membranous, none having yet been developed for protective covering, as in the beetle. The number of wings in every case was four, none having been dropped at that time.

Two groups were especially prominent, the cockroaches (Fig. 459 *B*) of which there were large numbers, some being as large as a finger, and many species; and the dragon flies (Fig. 459 *A*), which reached the great size of almost two and a half feet across the wings. The ab-

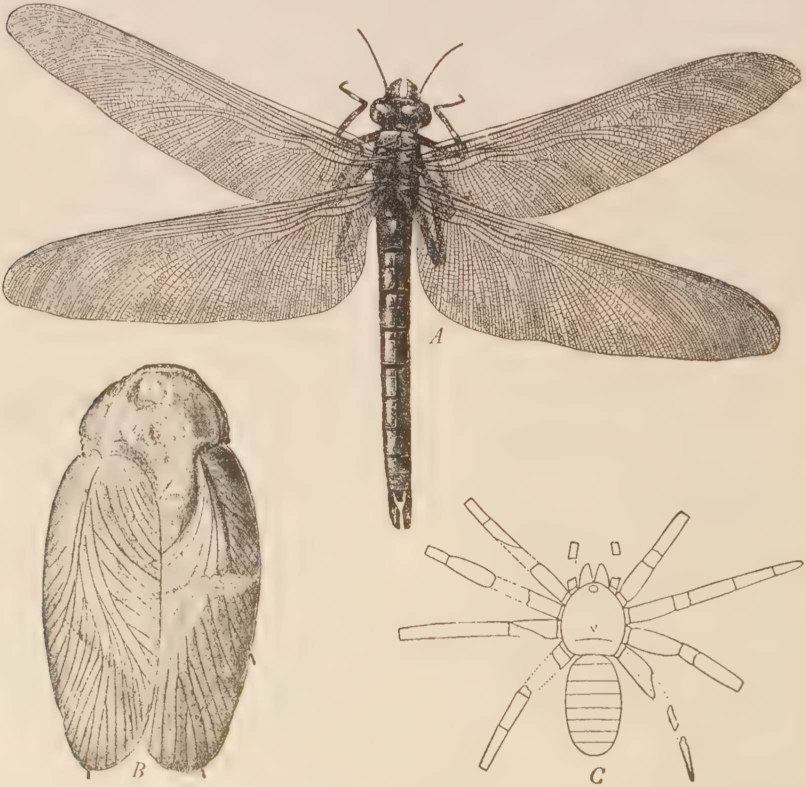


FIG. 459. — Carboniferous insects: dragon fly, *A*, *Meganeura monyi* (some of these were two and a half feet across the wings); *B*, *Adeloblatta columbiana;* *C*, spider, *Arthrolycosa antiqua.*

sence of all sucking insects, such as bees, wasps, and butterflies, whose food consists of the nectar of flowers procured by a sucking apparatus, and in fact of all insects which depend upon flowers for food is not surprising, since no flowering plants were in existence at this time.

The active dragon fly rather than the sluggish amphibian (p. 489) might seem "a far superior type of being, a far more promising candidate for the position of ancestor of the intelligent life which was to appear in the dim future." "But the insect had fulfilled the mechanical possibilities of which his structural organization was capable." (Matthew.)

VERTEBRATES OF THE CARBONIFEROUS

Fishes. — During the Mississippian sharks existed in an abundance which has not been equaled before or since, as is shown by the large number of species, of which nearly 300 have been described. Before the close of the Carboniferous, however, the number had become very small, only about 20 species being known in the Permian. As in the Devonian, the sharks are known from their fin spines and teeth (Fig. 460), the latter being of the crushing type. The sharks were, for the most part, small, being seldom more than five feet long, while none attained the size of their modern relatives.

FIG. 460. — A back spine, tooth, and scale of a Mississippian shark.

Only sharks and typical ganoids (Actinopteri) were important, the armored lungfish and fringe-finned ganoids having reached their climax in the Devonian.

Amphibians. — Next to the appearance of the fishes the most important event in the history of vertebrates was the rise of amphibians, of which the salamanders, newts, and frogs are modern representatives, since the ancestors of reptiles, of mammals, and even of man himself are to be found among them. Amphibians resemble reptiles, but differ from them in the fact that in the earlier period of life they breathe in water by means of gills,[1] like fishes; and it is only in the later period of life that they breathe air by means of lungs, like reptiles. The most important difference between fishes and amphibians is in the organs of locomotion, fishes having fins and amphibians legs, in the adult stage.

---

[1] Some amphibians never lose their gills.

It is hard to point out briefly all the differences between amphibians and reptiles, and it is indeed sometimes extremely difficult, if not impossible, to tell from the skeleton alone of extinct forms to which class a specimen belongs. One important difference, however, is to be found in the articulation of the skull to the backbone, which in amphibians is by means of two knuckle-like projections of bone (condyles) and in reptiles and birds by one. In fishes there is no movable articulation.

All Carboniferous amphibians belonged to the Stegocephali (Fig. 461) (Greek, *stege*, roof, and *cephale*, head), in which the skull was covered with bony plates, and the teeth were conical with walls that were sometimes highly infolded (Fig. 462). The limbs of most were weak and adapted more for crawling than for carrying the body well above the ground.

FIG. 461. — A Permo-Carboniferous landscape. The characteristic vegetation; two figures of the amphibian *Eryops* upon the land, each about seven feet long, are shown; a reptile (*Limnoscelis*) in the water; and a gigantic dragon fly in the air. (After Prof. S. W. Williston.)

Carboniferous amphibians varied greatly in size and shape, some attaining a length of almost eight feet. One characteristic genus, Eryops (Figs. 463 and 461), had a rather large, broad, flat head, and unevenly spaced, conical (labyrinthine) teeth, no neck, and a thickset body with broad, five-toed feet that were probably webbed. The tail was flattened vertically. Even with its roofed skull, Eryops would not look unlike an overgrown modern Japanese giant salamander, since the bones of the skull were covered with skin. It was able to crawl clumsily and slowly over the land, but must have been far more at home in the water. That this clumsy, small-brained beast should be one of the highest types of living beings of its time may help us to realize how remote the period was, and to what an extent vertebrate life has been evolved since then.


Fig. 462. — Cross section of the tooth of a *Stegocephalian.* Note complicated labyrinthine structure.

Some of the Carboniferous Stegocephali were armored and some had no protection; some had skulls nearly two feet long, while the skulls of others were not larger than one's thumb-nail; some had stout limbs, while the limbs of others were atrophied and the body elongated and snakelike.

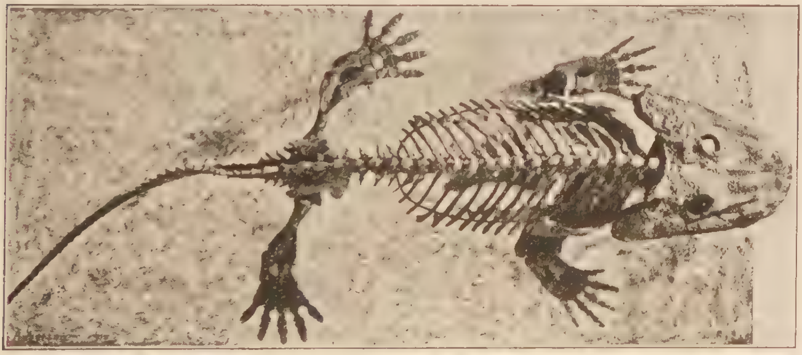


Fig. 463. — Top view of the skeleton of *Eryops,* a Permian *Stegocephalian.* The head is covered with the thick, bony plates characteristic of the order.

The commonest amphibian of the Carboniferous, Branchiosaurus (Fig. 464), did not differ greatly in appearance and habits from those of to-day. The teeth were small and conical, the eyes were protected by a movable ring of bony plates, and the lower surface of the body was covered with thin scales. The presence of gills in immature specimens shows that they lived in the water at least a portion of their life.

Certain Permian amphibians (Lysorphus) resembled a modern salamander (Amphiuma) in size, shape, and habits so strongly that it seems actually to have been related to it. So abundant are the skeletons of these amphibians in certain localities in the Permian strata of Texas that hundreds have been found embedded in nodules.

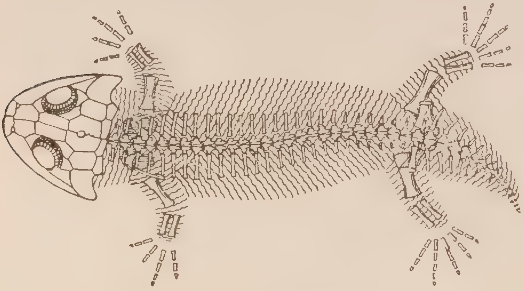


FIG. 464. — *Branchiosaurus*, a Carboniferous amphibian of small size occurring abundantly. The "roofed" head, the rings of bone about the eyes, and the scaly covering of the lower side are shown.

Amphibians are known from their footprints to have lived in the Devonian. The knowledge which can be gained of the animal and of the conditions under which he lived is well illustrated in the footprints preserved in one layer of Mississippian (Mauch Chunk) shale near Pottsville, Pennsylvania.

> "There is a succession of six steps, along a surface little over five feet long; each step is a double one, as the hind feet trod nearly in the impressions of the fore feet. The prints were hand-like; that of the fore foot five-fingered and four inches broad; that of the hind foot somewhat smaller and four-fingered. That the Amphibian was therefore large is also evident from the length of the stride, which was thirteen inches, and the breadth between the outer edges of the footprints eight inches. There is also a distinct impression of a tail an inch or more wide. The slab is crossed by a few distinct ripple marks (eight or nine inches apart) which are partially obliterated by the tread. The whole surface, including the footprints, is covered throughout with raindrop impressions.
>
> "We thus learn that in the region about Pottsville a mud flat was left by the retreating waters, perhaps those of an ebbing tide, covered with ripple marks; that the ripples were still fresh when a large Amphibian crossed the flat; that a brief shower of rain followed, dotting with its drops the half-dried mud; that the waters again flowed over the flat, making new deposits of detritus, and so buried the records." (Dana.)

Origin of Amphibians. — Several lines of evidence show that amphibians may have been descended from the fringe-finned ganoids (crossopterygians): (1) the teeth of both are often labyrinthine

(Fig. 462); (2) the bones of their skulls are similar in position and arrangement; (3) some primitive amphibians have rings of bony plates (sclerotic plates) about the eyes; (4) the structure of the fin of the fringe-finned ganoids was such that a leg might have been formed from it by modification.

Rise of Amphibians. — The rise of amphibians was a momentous step in the evolution of life, but it was not a surprising one. Fishes were the predominant race of the Devonian, and it was to be expected that the structure of some of them would in time become modified to take advantage of the realm of the lands where food was either more easily obtainable or of a more nutritious quality than in the seas, or where the competition was less keen. The extensive swamps of the Devonian and Carboniferous and the shiftings of the seas have been assigned as the immediate causes of the rise of the amphibians from fishes. It seems more probable, however, that during every period of the Paleozoic, swamps and shallow water were present, in which amphibians would have been evolved had fishes been present which were so constructed that by slight modifications they could become adapted to land conditions. How this was accomplished is shown in the development of the individual amphibian, which in the tadpole stage is physiologically a fish, but which later breathes by means of a simple sack-like lung instead of gills. It is important to note that the Carboniferous amphibians, more than their modern relatives, possessed characters closely allying them to the fishes, and that their fishlike characters were more like those of Devonian than of modern fishes.

Some doubtful amphibian tracks have been found in the Devonian, but no bones earlier than the Carboniferous have been discovered. However, the well-developed limbs of the earliest species indicate a line of ancestors that lived in the Devonian. Amphibians attained their greatest importance in the Carboniferous (Pennsylvanian and Permian) and have taken a very subordinate place since the Triassic. Even before the close of the Pennsylvanian they had begun to give place to the reptiles.

Reptiles. — The reptiles of the Permian were even more varied than the amphibians and have been placed in three groups. The first group (cotylosaurs) includes the most primitive reptiles known, its members differing from other reptiles, among other particulars, in having a roofed-over skull. All the members of this class that are known had very short necks; short, stout limbs; rather heavy bodies, and usually long tails (Fig. 461). Some had long, sharp, curved teeth (Labidosaurus, Fig. 465) arranged in two or more rows, which were probably used for prodding in the mud for soft-bodied invertebrates, and for crushing; some had conical teeth in front and crushing teeth behind; and some had a mouth filled everywhere on jaws and palate with short, stumpy teeth, suitable only for crushing shellfish; while others had slender teeth indicating insectivorous habits. In some, the claws terminated in flattened nails, while in others the claws were sharp and curved. The habits of this group varied somewhat, some being more terrestrial than others, but all probably lived in swampy places and about lagoons.

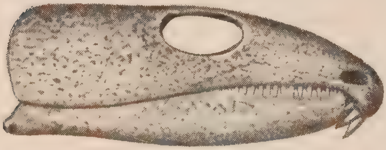


Fig. 465. — The head of a Permian reptile, *Labidosaurus*.

A second group of Carboniferous reptiles (pelycosaurs) had lighter skulls than those of the first group; larger necks; longer, better-formed legs and feet, and usually longer tails. The best known of these (Dimetrodon, Fig. 466) was about 10 feet in length and was especially characterized by a finlike crest on the back formed by spines of its vertebræ. The skull had strong, sharp, carnivorous teeth, indicating that the creature was a fierce, predaceous animal. The use of the crest on the back is unknown, and aside from its presence the animal was very primitive in structure. Some members of this group (Varanosaurus, Fig. 467) were swift-running reptiles, living in the forests, hiding under logs, and feeding on the numerous cockroaches and other insects.

Fig. 466. — *Dimetrodon*, a spiny but primitive reptile from the Permian of Texas. (Modified after Jaekel.)

A third group, although inconspicuous in the Permian, were of great importance both because of their great development in the

Triassic and also because they were the probable ancestors of the mammals. They were small reptiles with short but strong legs and large heads. The mammalian characters are to be seen in the skull, the teeth, and other parts of the skeleton. This important group is described more fully in the following chapter (p. 536).

FIG. 467. — *Varanops*, a Permian reptile forty-four inches long, on a *Sigillaria* log. (After Prof. S. W. Williston.)

Rise of Reptiles. — The rise of reptiles from amphibians was a logical sequence. On account of their aquatic larval life, amphibians were restricted to the vicinity of the water, while reptiles, because of the development of a firm eggshell and the omission of the aquatic stage of the young, were able to populate the dry lands and thus to take advantage of many kinds of food. Amphibians may indeed be considered as transitional forms by which reptiles were evolved from fishes.

The rapid development of this class after it was once well-started was probably due to its higher organization, to the lack of competition in the new surroundings, and to the abundance of food. It has been suggested that the purification of the air as a result of the withdrawal of carbon dioxide in the formation of coal produced an atmosphere which was more favorable for the development of air-breathing animals, but the amount of carbon dioxide withdrawn does not seem to have been sufficient to have made a great difference.

CARBONIFEROUS PLANTS

The forests of the Carboniferous were very different in appearance from those of to-day. None of the trees common at present in the forests and swamps were in existence, flowering plants were conspicuous by their absence, and even grasses and mosses were lacking. The living relatives of the Carboniferous trees are for the most part lowly, inconspicuous plants.

The land plants of the Carboniferous belonged to six great groups: (1) ancestral ferns, (2) seed ferns (pteridosperms), (3) club mosses (lycopods), (4) an ancient extinct group, the sphenophylls, (5) the horsetails (Calamites), and (6) the Cordaites and possibly some conifers.

(1) **Ancestral Ferns and** (2) **Seed Ferns.** — The shale overlying coal beds is often full of the fronds of fernlike plants (Fig. 468), and so perfect is the preservation of some of them that the finest venation is shown. The beauty of such fossils is especially striking when the shale is light in color, since under such conditions the delicate outline of the black fossil frond is brought out with great distinctness. It was formerly thought that these fernlike leaves were the remains of ferns, but a more careful study and further discoveries have shown that few are true ferns; on the contrary, the great majority belong to an extinct family, the seed ferns or pteridosperms.

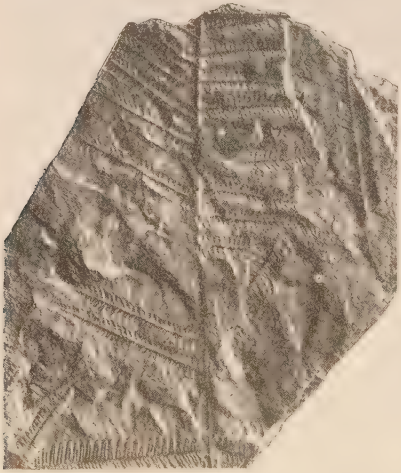


FIG. 468. — A Paleozoic fernlike plant, *Pecopteris*.

The important difference between these families lies in the reproduction, the true fern producing spores and the pteridosperms, seeds.

Ancestral Ferns. — The most important family of Paleozoic ferns (Marattiaceæ) has descendants living to-day, but the Paleozoic members of the family were tree ferns, reaching in some species a height of upwards of 60 feet. This great family has dwindled to a few genera which are now confined to the tropics; one of which, however, the elephant fern, sends up huge fronds to a height of 10 or 12 feet. In addition to the tree ferns there were doubtless low, herbaceous ferns, living under the same conditions as the ferns of to-day.

Seed Ferns (*Pteridosperms*). — The members of this extinct group, if living to-day, would probably be called ferns by the casual observer, but a careful examination would show that instead of having small sporangia on the back of the fronds they bore seeds, sometimes as large as hazelnuts, which were surrounded by a thick, fleshy outer coat. The pteridosperm group (Fig. 469) is interesting as a connecting type, since it is a link between the ferns, on the one hand, and the cycads, which were the dominant plants in the Mesozoic, on the other. Whether it stands as a connecting link between the ferns and the great groups of higher plants, or whether it leads to the cycads and stops there, cannot as yet be affirmed.

FIG. 469. — *Lyginodendron.* Restoration showing the stem, roots, and foliage; *a*, seeds; *b*, disks and pollen sacks. (After Mrs. D. H. Scott.)

FIG. 470. — Restoration of *Lepidodendron*, showing the position and character of the leaves, the fruit, and the diamond-shaped markings on the trunk. (See also Fig. 471.) Compare the branching of *Lepidodendron* with that of *Sigillaria*.

(3) **Club Mosses (Lycopods).** — The conspicuous trees of the Carboniferous were gigantic club mosses, some of which grew to a height of more than 100 feet. One of these, the Lepidodendron (Greek, *lepis*, scale, and *dendron*, tree) was freely branched (Fig. 470)

and had, consequently, somewhat the general outline of our forest trees, but with that the resemblance ended. The leaves were numerous and slender and were commonly arranged in oblique rows about the trunk and branches. When shed, their bases left diamond-shaped scars which gave a characteristic appearance to the bark (Fig. 471). The largest Lepidodendron trunk yet described was found to be 114 feet long up to the point where it began to branch; the diameter of the base was about three feet, while at a height of 114 feet it was one foot, showing that it was a tree of slender proportions. Other species, however, were of a somewhat sturdier build.

The Sigillaria (Latin, *sigillum*, seal) differed externally from the Lepidodendron, especially in two particulars; it branched sparingly (Fig. 472) and the leaves were arranged in vertical rows (Fig. 473), the leaf scars on the bark giving rise to the name " seal tree." In some species the leaves were a yard long. Sigillarian trunks almost as slender and high as those of the Lepidodendron have been found, but, as a rule, they were shorter and

FIG. 471. — Impression of the bark of the *Lepidodendron*, showing the leaf bases and characteristic diamond-shaped scars. (See Fig. 470.)

FIG. 472. — Restoration of *Sigillaria*, showing the position and character of the leaves and the fruit, and the peculiar bark. (See Fig. 473.) Some of them grew to a height of a hundred feet, with a diameter of six feet.

stouter, one specimen six feet in diameter and 18 feet high having been described.

The fruit of both the Lepidodendron and Sigillaria was in the form of well-defined cones that were usually borne at the ends of the smaller branches. In the clay underlying coal seams the "roots" or underground stems of the lycopods often occur and are called Stigmaria.

The trunks of the lycopods consisted of a hard, woody rind and a soft, cellular interior which quickly decayed. As a result of this structure the fossil trunks seldom show their original cylindrical form, but are usually flattened into thin sheets.

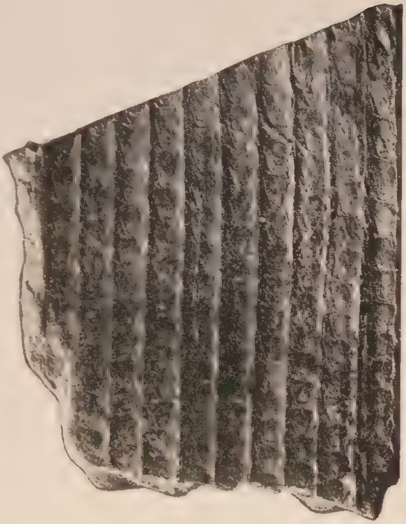


FIG. 473. — Bark of *Sigillaria*, showing the vertical arrangement of the leaves and the fluted surface.

The great lycopods of the Carboniferous are now represented by the insignificant ground pine and Selaginella.

The coal beds of the Carboniferous are largely composed of Lepidodendron and Sigillaria remains. Some coal of this period (cannel), however, is made up chiefly of spores of Carboniferous plants.


FIG. 474. — Stem and leaves of *Sphenophyllum*, a slender plant, the stem seldom exceeding two fifths of an inch in diameter. The sphenophyllums probably supported themselves by limbing.

(4) **Sphenophylls.** — This extinct group is interesting because it suggests a common ancestor for the lycopods and horsetails (Equisetales). The plant had a slender, ribbed stem, seldom more than a quarter of an inch in diameter, which bore delicate, wedge-shaped leaves (Fig. 474) attached in whorls to the stem by their ends. Sometimes the leaves were deeply cut, making them almost hairlike in appearance. These plants probably had a trailing habit, or perhaps supported themselves on stronger plants. Sphenophylls bore cones somewhat like those of the Calamites.

(5) **Horsetails (Calamites).** — Except for their greater size, the horsetails of the Carboniferous had much the appearance of the lowly horsetail or scouring rush of to-day and were, indeed, related to it. The tree horsetails of the Paleozoic are called Calamites (Fig. 475), from the most important genus of that time. They were trees which reached a height of 60 or more feet and were almost as conspicuous as their Lepidodendron and Sigillaria neighbors. Their habit of growth appears to have been similar on a glorified scale to that of some of their living relatives. Some were simple shafts, while others were probably gracefully branched trees with many boughs.

Fig. 475. — *Calamites.* They seem to have had habits similar to those of the horsetails of to-day. (See Fig. 476 *A* and *B*.)

The bark (Fig. 476 *A*) of the Calamites had characters which readily distinguished it from other trees of its time. The stems were ribbed, the ribs ending at each "node" and a new set continuing beyond the node to the next, when an alternate set again appeared. The leaves (Fig. 476 *B*) were simple and were attached to the nodes in whorls. Conelike fruits were borne at the ends of the twigs and contained spores of one kind.

Calamites began in the Devonian and went out with the Paleozoic, but the horsetails of the Mesozoic were transitional, both in size and in structure, to the modern horsetails.

(6) **Cordaites and Other Gymnosperms.** — The trees of this group were the most highly developed of the Paleozoic forests. They were large trees (Fig. 477) which sometimes grew to be 100 feet in height and were easily distinguished from the other trees of the time by the large, sword-shaped leaves which were borne in a crown on the top of the main trunk. Some specimens of Cordaites leaves exceed three feet in length and closely resemble the leaves of such plants as the lily and Indian corn, although not related to them. The fructifications, which were borne in a poorly developed cone, were of two kinds, male and

female, the latter having a fleshy cover somewhat like a plum. Cordaites were on a level with the seed ferns as regards seeds, but in the structure of the wood and in other respects they were more highly organized. Cordaites became extinct before the close of the Paleozoic, unless the ginkgo (p. 507) or maidenhair tree is a descendant.

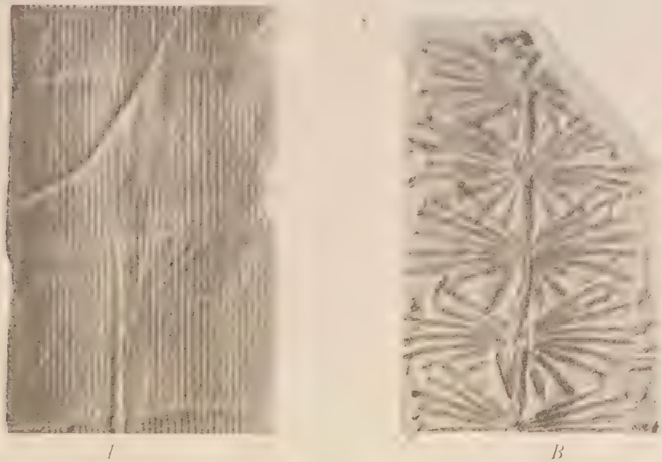


FIG. 476. — *A*, portion of trunk of a *Calamites*. The nodes and vertical striations are characteristic. Some grew to be sixty to ninety feet high. *B*, *Annularia*, showing the characteristic arrangement of the leaves of the Calamites.

True conifers possibly appeared before the close of the Paleozoic, as the presence of the genus Walchia (Fig. 478) in the Permian appears to show.

Conditions under which the Coal Plants Grew. The most abundant plants of the Carboniferous swamps, the Calamites, Lepidodendron, and Sigillaria, had narrow leaves with a small surface exposed to the sun. At the present time plants with leaves of this character grow in the bright sunlight, while the leaves of shade plants are large, the greater size being necessary in order that they may be acted upon by a larger amount of light. Some of the coal plants, such as the true ferns and seed ferns, had fairly large leaves, but they were not of unusual size, indicating that they were only partially shaded by the small-leaved Calamites and Sigillaria. From this evidence it has been held that the Carboniferous plants did not live in a misty atmosphere through which the sun's rays penetrated with difficulty, but in one which was not unlike that of the present.

FIG. 477.—*Cordaites.* Large trees with long, narrow leaves sometimes a yard in length. They are allied to the conifers as well as to other orders of plants.

The character of the foliage of the coal-making plants may, however, have been an adaptation to conditions which more than counterbalanced the effect of bright sunlight. Their roots were those of water plants, and their leaves were not only narrow but were supplied with various devices for preventing the loss of water by rapid transpiration. "If the water they grew in had been fresh, they would not have had such leaves, for there would have been no need for them to economize their water (which is physiologically usable in only small quantities in the plant), but as we see in bogs and brackish water to-day, plants only partly submerged protect their leaves from transpiring largely." (Stopes.)

FIG. 478. — Stem and leaves of *Walchia*, a characteristic Permian conifer.

The evidence at hand (p. 472) points to the existence of extensive swamp areas which slowly sank as the half-decayed vegetation accumulated on them, and which were so near sea level that a slight sinking killed the vegetation growing there and buried them under sand, clay, or lime ooze. It is probable, therefore, that the coal plants (Calamites, Lepidodendron, Sigillaria) of the Carboniferous lived not only in fresh but even grew out in the brackish water of the shallow interior seas.

COAL

Coal occurs in very thin beds in the Devonian and in thicker beds in the Mississippian, but it is in the Pennsylvanian or Coal Measures that it occurs for the first time in beds or *seams* thick enough to be of commercial value. The thickness and purity of the coal beds of this period are such as to make it the most important of all coal-bearing systems.

Mode of Occurrence. — The total thickness of the Pennsylvanian or Coal Measures is 4000 to 5000 feet in the Appalachian Mountains and 18,000 feet in Arkansas, but of this great accumulation of sediment seldom more than two per cent. is coal, the remainder being sandstone, shale, limestone, and iron ore. In the section shown in Fig. 449, p. 473, it is apparent that there is no regular order of succession of the beds, except that often a bed of fire clay immediately underlies a coal seam. It is also usual to find shale immediately overlying the coal, although this does not invariably happen. In different portions of the same field the same order is usually found, but in separate basins the order may vary greatly and is probably never the same in all particulars.

Origin of Coal. — Coal is of vegetable origin, as is proved (1) by a microscopic examination which, even in dense anthracite, shows the cellular structure of plant tissue, and (2) by stumps of trees with their roots penetrating the underclay which sometimes underlies the coal seam. In South Wales, for example, there are 100 coal seams in which such stumps are embedded. In Nova Scotia, of 76 coal seams 20 have upright stumps with spreading roots penetrating the clay; in the United States few such occurrences are known. (3) Leaves are often beautifully preserved in the shale immediately overlying the coal. (4) Fire clay often, although not invariably, underlies coal beds. The character which a fire clay possesses of withstanding intense heat is due to the absence of alkalies, such as potash and soda, whose withdrawal was brought about by the plants whose roots removed the soluble salts which they required for food or which were removed by the leaching action of the water in the lakes or lagoons.

It is evident, therefore, that coal is compressed bituminized or mineralized vegetable matter.

Necessary Conditions for Coal Formation. (1) *How Vegetable Tissue Accumulated.* — It is generally believed that coal originated, for the most part, from vegetation that grew in swampy or marshy places, although evidence has been advanced recently which shows that much coal was formed from organic matter, spores, wood, and leaves, carried into swamps and lakes. It is a matter of common observation that wood decays much less rapidly below water than above it. This is shown by piles and posts which may be entirely rotted away where exposed to the air, while they are well preserved where continually soaked with water. The reason is to be found in the fact that vegetation in the open air is readily attacked by destroying fungi, the carbon is oxidized to carbon dioxide and the hydrogen to water, and as these are volatile the entire substance of the plant may disappear; while in water the oxidation proceeds much less rapidly and completely, and wood-destroying organisms cannot flourish in water. Of the vegetation of luxuriant forests only thin layers of humus remain, and the abundant vegetation of dry, fertile plains fails to accumulate, although the slow-growing bog moss (sphagnum) of cold regions may accumulate to form thick beds of peat.[1]

(2) *How it was Kept from Decay.* — The chemical changes which take place in vegetable tissue (which has a composition approximately of $C_6H_{10}O_5$) when deposited in water, result in the formation of marsh gas (CH_4), carbon dioxide (CO_2), and other gases. The effect of these changes consists in (1) a reduction in volume, (2) a reduction in the volatile constituents, (3) a reduction in the amount of water, and (4) a relative increase in the percentage of carbon, since although the greater part of the hydrogen and oxygen are removed, the carbon is only moderately reduced.

The proof in support of the assumption that the great coal deposits were developed in swamps, the vegetation accumulating where it

---

[1] "The peat-bog hypothesis, or growth *in situ* (autocthonous) hypothesis, at the present moment has won the adhesion of the majority of the geologists, although it encounters the serious difficulty that peat bogs are not found in the parts of the earth which at the present time present the nearest approach to the conditions of climate obtaining in the great coal-forming epochs. The lacustrine or transport hypothesis, which is better applicable to the conditions of warmth which are generally conceded to have existed in the most active periods of coal formation, has had few adherents in recent years outside of France. It is, however, the hypothesis which harmonizes best with the structures found in coals as the result of microscopic examination. The bottom of every lake is filled with countless pollen grains or spores. As the bottom becomes shallower, water lilies and other water plants make their appearance and add their remains to the lacustrine accumulations. Finally the coarser débris of the land plants is added to the heap and not long afterwards mosses, grasses, sedges, heaths, and ultimately forest trees, may flourish, where once was open water." Jeffrey, E. C., — *On the Composition and Qualities of Coal: Economic Geology*, Vol. 9, 1914, pp. 730–742.

It is believed by this investigator that practically all coal is floated material and has not originated from plant remains *in situ*, and microscopic evidence is stated by him to place this as reasonable beyond question.

grew, is to be found (1) in the basin-shaped seams which are often thickest in the center and thin out to black shale at the edges; (2) in the remains of aquatic animals in the midst of the coal; (3) in the roots of trees embedded in the underclay in the position in which they grew; and (4) in the purity of the coal. If the coal was formed from vegetation that had drifted together, it would contain sand or mud in appreciable amounts. It is not unusual, however, to find coal with no more impurities (ash) than the wood from which it was derived would have contained. The nearly uniform thickness of the coal beds over hundreds of square miles is also offered as an objection to the theory that the vegetable matter was drifted together.

(3) *How it was Changed to Coal and what Varieties Resulted.* — The principal varieties of coal are peat, the partially decayed vegetation of swamps; lignite or brown coal; bituminous or soft coal; and anthracite or hard coal. All have been derived from peat, lignite being the second stage, bituminous the third, and anthracite the fourth. The last stage is graphite, in which all the volatile constituents have disappeared and pure carbon only remains. Anthracite coal occurs in regions where the strata have been much folded and faulted. It is therefore generally believed[1] that the heat and pressure of dynamic action are essential processes in coalifaction or bituminization. It has also been suggested that in regions of great folding the fractures which have been produced facilitate the escape of gases from coal and thus hasten the process. In Rhode Island dynamic metamorphism has been so intense that the coal has gone beyond the anthracite stage and contains so much graphite as to be of little value. In Colorado and elsewhere bituminous coal has been converted to anthracite where cut by dikes, and in Mexico coal has been baked to graphite by heat. Such graphite is of great value in the manufacture of lead pencils. Some varieties of coal result from the kind of vegetation of which it is composed. Cannel coal, for example, is made almost wholly of the spores of Carboniferous plants.

Conditions Favoring Coal Formation in the Pennsylvanian. — To understand the great accumulation of coal during the Pennsylvanian one must picture to himself the conditions at that time. The land appears to have been low, and sluggish streams meandered through extensive fresh-water marshes. The great inland seas, shut off on the east by the continent of Appalachia, were bordered by wide

---

[1] Prof. E. C. Jeffrey offers evidence to show that the varieties of coal depend largely upon their composition.

fresh and salt water marshes in which vegetation flourished. Similar conditions are to be seen to-day in the Dismal Swamp of Virginia, on the coast of New Jersey, the Carolinas, and Florida.

Since less than five per cent. of the Coal Measures (Pennsylvanian) consist of coal, the greater part of the system being composed of sandstones, shales, clays, and in some localities limestones, it is evident that subsidence accompanied deposition. The submergence was not continuous, however, but was interrupted by many halts, with occasional slight elevations. When the sea bottom was built up sufficiently, plants grew on it, and salt water marshes, which eventually became fresh, appeared. In the course of years the trees fell, and upon their fallen trunks others grew up. In the process of time their remains made thick beds of peat. A too rapid subsidence inundated the swamps, killing the vegetation, and the peat was then covered with sediment. If the water was far from shore, beyond the reach of mud and sand, limestones were deposited; if close to shore, mud and sand were laid down. When the downward movement ceased, the bottom of the sea was built up until it again became shallow enough to permit plants to grow on it. The order of deposition shown in Figure 449 (p. 473) is thus explained. As has been stated, an elevation sometimes occurred, as is shown by unconformities. Some of the unconformities, however, were produced merely by the shifting of the stream channels in the swamps.

The number of coal beds in any vertical section varies greatly: in Pennsylvania and Nova Scotia as many as 30 are known, while in Illinois there are often less than 10. Some of these beds are workable, but many are not.

Extent and Structure of Coal Beds. — Individual coal swamps of the Pennsylvanian were very extensive. The Pittsburgh coal bed, one of the greatest in the world, extends over an area of at least 12,000 square miles in Pennsylvania, Ohio, and West Virginia. The extent of some modern peat bogs compares favorably with those of the Pennsylvanian, but their thickness is much less. One extends across Holland and Belgium into France, and the Alaskan tundra has a much greater continuous area than the largest of those known in the past. All coal beds are not of great extent, some corresponding to the small peat bogs of to-day: one basin 200 yards in diameter was found to have two coal beds, one two and the other 16 feet in thickness; and another one 115 yards in diameter was found to have a coal seam eight feet in maximum thickness. A given thickness of coal represents only about five per cent. of the original thickness of the peat bed, consequently a coal bed 16 feet thick represents a peat bed about 320 feet in thickness. None of the peat bogs of the present have the great thickness of peat necessary to make great beds of coal.

The commercial importance of Great Britain and much of the remarkable development of the United States are due to the presence of abundant and accessible supplies of coal.

Climate during the Deposition of Coal. — Since coal occurs not only in the temperate zones and in the tropics but even in the polar regions, it has been assumed that the climate of the Pennsylvanian was uniform throughout the world. This is further borne out by a study of the structure of the wood, which shows no rings of growth such as are developed in plants living in a climate in which there are dry and wet or cold and warm seasons. The question as to the temperature and the amount of moisture has given rise to some discussion. It has been generally assumed that the large size of many of the trees and the accumulation of their remains in swamps are proofs of a warm, humid climate. The thickness of the coal seams has also been considered confirmatory evidence. Several objections have been offered to this belief, however. (1) At present the great accumulations of peat are in cold, temperate climates. (2) Peat is rarely formed of rapid-growing plants but chiefly of the remains of such plants as sphagnum moss. (3) It has been pointed out that, as a whole, the leaves of Carboniferous plants bear a resemblance to those of living plants that are adapted to dry (xerophytic) conditions (p. 497), being narrow and possessing devices to prevent the rapid evaporation of water. In the tropics peat accumulates more from tree trunks and leaves which have been floated into lakes and marshes, and little from moss or trees that grew *in situ*.

When all the evidence is considered, there seems little doubt that the climate of the regions in which coal accumulated was moist and warm, although not tropical.

REFERENCES FOR COAL

Jeffrey, E. C., — *The Mode of Origin of Coal:* Jour. Geol., Vol. 23, pp. 213–230.
Moore, E. S., — *Coal,* 1922.
Stevenson, J. J., — *Formation of Coal Beds*
Tonge, James, — *Coal.*
White, David, — *Origin of Coal:* Bureau of Mines, Bull. 38.

Problems of the Permian

No other period of the earth's history offers so many unsolved problems as the Permian. These problems have to do with the climate and the life of the period.

(1) Why was the Permian so fatal to marine life? During this time the invertebrate life, for the most part, either became extinct or was much modified in important structural features. The impoverishment of the life is shown in the estimate that the number of Permian species was only two per cent. of that of the combined Mississippian and Pennsylvanian. One factor in the extinction of such a large percentage of species was doubtless the emergence of the continent and the consequent withdrawal of most of the epicontinental seas. This drove the life of the warm, shallow seas into the coastal waters of the ocean, where it was not only obliged to compete with other species but was compelled to live under conditions to which it was not accustomed. Such a radical change in environment was, doubtless, fatal to many species, and it is consequently not surprising that a large number disappeared. The faunas in the restricted epicontinental seas were crowded, and competition was severe. Where such seas persisted, as in India and California, the change in the fauna was gradual and no satisfactory dividing line can be drawn.

A further result of the elevation of the continents (or withdrawal of the seas) was possibly the changing of the position of the ocean currents, which were forced to take new courses. The extinction of some of the plant food upon which the animals of the epicontinental seas ultimately depended would have had a marked effect on the life. These and other causes may have combined to bring about the sweeping changes in the invertebrate life at the close of the Paleozoic.

The land vertebrates did not suffer as did the invertebrates. This may have been due (1) to the greater land area over which they could spread and the greater variety of conditions open to them; (2) to the greater variety, or more suitable varieties, of plants and insects which they could use for food; or (3) to their better organization. During this time, so fatal to the marine fauna, the amphibians continued in abundance and the reptiles became supreme.

The plant life also suffered a great change: the important Carboniferous groups became extinct, or nearly so, and their places were taken by plants of a more modern type. Whether this was due to the draining of the swamps, with the resulting death of the swamp vegetation, or to the spreading of upland trees which existed in the Pennsylvanian but of which nothing is now known, cannot be stated. Once well-established, however, the more highly organized upland plants probably became in time suited to swamp conditions and occupied the places formerly held by the lycopods and horsetails.

(2) Why was the Permian a period of glaciation, and in particular, why were the areas affected not only near the equator but near sea level?

Various explanations have been offered, but none has a general acceptance. One is based on the assumption that the carbon dioxide contents of the air was decreased. The depletion of carbon dioxide is believed, by the adherents of this theory, to have been the result of a combination of causes, indirectly because of the elevation of the continents and an increase in the land area. As a result of a greater land surface being exposed to the agents of the weather, the rocks upon weathering extracted much carbon dioxide from the air. The depletion of this gas was further hastened by the oceans, which are believed by the supporters of this theory to have absorbed great quantities of carbon dioxide. The air was also freed of its carbon dioxide during the accumulation of coal. One doubtful element in the theory is the efficacy of carbon dioxide in retaining heat.

Another solution of the problem is found in the amount of water vapor in the atmosphere, since water vapor is known to act as a blanket in retaining heat. The enlarging of the land area decreased the amount of water vapor in the atmosphere and thinned the thermal blanket.

(3) Why was the climate generally arid in the northern hemisphere during the Lower Permian? The great extent of land and the narrowing of the oceans undoubtedly had a marked effect in producing an arid climate, since less moisture would have been evaporated and it would have been precipitated over a wider area.

(4) Why was the great Appalachian system raised at this time? It is usually stated that strains had been accumulating in the earth's crust throughout the Paleozoic and that these strains were relieved by the folding of the Appalachian trough at its close, but this does not fully answer the question.

SUMMARY OF THE PALEOZOIC ERA

The Building of the Continents. — The continent of North America was probably covered by seas in every part during some portion of the Paleozoic, but two areas seem to have been especially free from epicontinental seas during all but perhaps a small part of the era. These areas lie in the Laurentian region of eastern Canada and in the southeastern United States, where the continent of Appalachia formerly stood and of which the Piedmont Plateau is a part. During this era the seas varied greatly in extent and in position. In only a few areas, notably in the Appalachian trough and in the Great Basin region, did they persist through the greater part of the Paleozoic.

Evolution and Extinction of Life. — A study of the accompanying table (Fig. 479) brings out some important points concerning the life of the era. It is seen that certain classes began, or at least are first known, in the earlier periods, culminated in the later periods, and then after several periods of struggle became extinct. If one were to make a careful study of each of these classes it would be found that the genera of each class had a shorter life than the class as a whole, and that the species had a still briefer one. It would also be found that striking evolutional changes took place during their life histories. It is also to be seen that some classes gradually increased in importance throughout the era, while others were inconspicuous in the

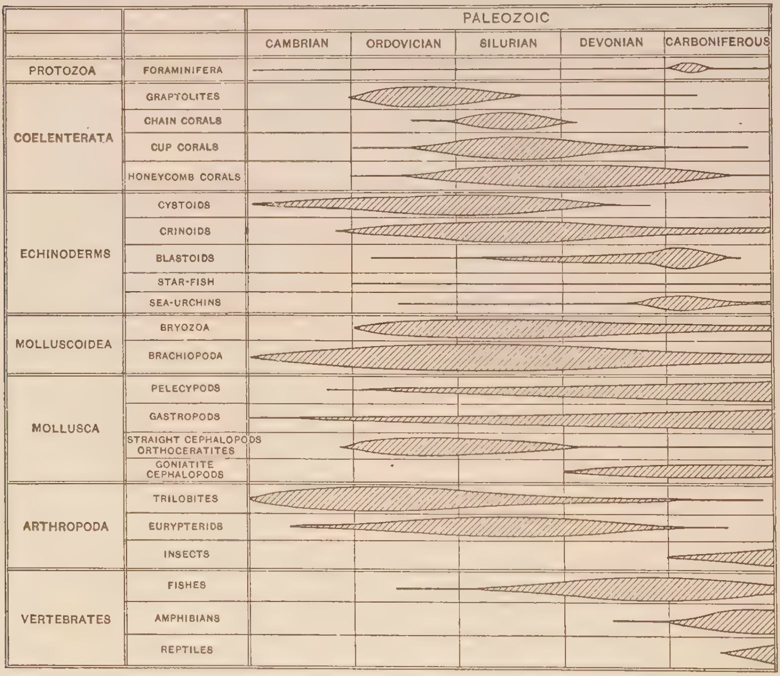


FIG. 479. — Table showing the distribution and relative abundance of the life of the Paleozoic.

Paleozoic, but if a Mesozoic table were examined it would be found that these inconspicuous forms became prominent in the latter.

Climate. — Our knowledge of the climate of the Paleozoic is not extensive. As a whole, the evidence points to uniform conditions and no well-marked climatic zones. There were, however, glaciers in certain regions in the Cambrian and Permian, and perhaps in other periods. Certain areas were arid during portions of the Paleozoic, as their red sediments, gypsum, and salt show, the aridity having probably been caused in most regions by elevated land areas which shut off the moist winds of the oceans.

REFERENCES FOR THE CARBONIFEROUS PERIODS

Blackwelder and Barrows, — *Elements of Geology*, pp. 369–396.
Chamberlin and Salisbury, — *Geology*, Vol. 2, pp. 496–677.
Grabau, A. W., — *Textbook of Geology*, Vol. II.
Pirsson and Schuchert, — *Text-Book of Geology*, Vol. II.
Schuchert, Chas., — *Paleogeography of North America:* Bull. Geol. Soc. America, Vol. 20, 1910, pp. 494–498.
Scott, W. B., — *An Introduction to Geology*, pp. 609–654.
Ulrich, E. O., — *Revision of the Paleozoic Systems:* Bull. Geol. Soc. America, Vol. 22, 1911.

CHAPTER XX

MESOZOIC ERA: THE AGE OF REPTILES

The Mesozoic is divided into four periods, as given below:

Cretaceous Periods	Upper Cretaceous Lower Cretaceous (Comanchean)	The word comes from the Latin *creta*, meaning chalk, because of the great thickness of the chalk of this period in England and France.
Jurassic Period		So named because of the fine development of the strata of this period in the Jura Mountains.
Triassic Period		So named because of the threefold development in Germany where the strata were first carefully studied.

Physical Geography during the Mesozoic

Triassic

Atlantic and Gulf Coasts. — A number of points seem to be well established concerning the distribution of land and water in North America during the Triassic (Fig. 480). (1) The complete absence, so far as known, of marine sediments from the eastern half of the continent indicates that the coast line was farther east than now and that during the entire period the lands were being reduced by erosion. Indeed, it is possible that not only Newfoundland but even Greenland and Iceland were united to the continent. (2) The presence of Triassic rocks in long, narrow bands roughly parallel to the Atlantic coast, that stretch from Nova Scotia to North Carolina, the longest of which extends from the Hudson River across New Jersey, southeastern Pennsylvania, through Maryland and Virginia, formerly gave rise to the opinion that these deposits were formed in tidal estuaries whose waters for the most part were brackish or nearly fresh. It seems more probable, however, that the deposits were not formed in continuous water bodies but in river basins analogous to the Great Valley of California. These continental deposits were formed by the confluence of alluvial fans (p. 124) made by streams flowing from higher land at the margin of the area; deposits formed by rivers meandering over the lowland; lake deposits in places where the drainage was obstructed, as in Tulare Lake, California; and it is possible that parts of the area were covered by tidal waters and that in such places estuarine deposits were laid down. Since the region was in an arid or semiarid condition, deposits of wind-blown sand were doubtless laid down on land, some of which probably constitute a part of the Triassic sandstone.

FIG. 480. — Map showing the probable outline of North America during a portion of the Upper Triassic. The continental deposits are shown in solid black. (Modified after Schuchert.)

These basins were separated from the Appalachian Mountains on the west by ridges of crystalline rocks (Fig. 481). The presence of high land between the basins and the Appalachians is shown by the composition of the sediments laid down in the depressions, which were

FIG. 481. — Section through the Connecticut valley and adjacent region in Massachusetts. *Js* is Triassic sandstone. (After Emerson.)

not derived from sedimentary rocks, as would have been the case if the Appalachians had drained eastward through them, but are granitic and were derived from metamorphic and igneous rocks. The present thickness of these deposits is very great, it being estimated that some of those of Pennsylvania and Connecticut are several thousand feet thick. The liability to error in estimating the thickness of these deposits, because of the concealed faults, is so great that no figures can be considered more than provisional. The sediments north of Virginia are usually red sandstones and shales, with occasional thin beds of black shale and limestone.

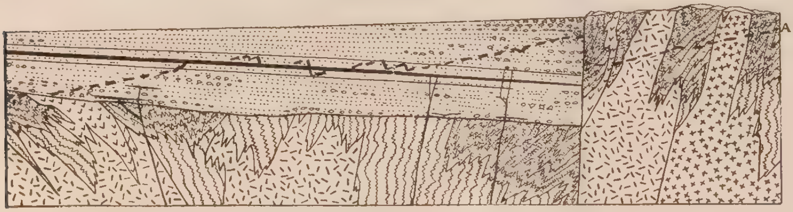


FIG. 482. — Section across the Connecticut valley, showing the thick strata of sandstone (dotted) and the lava beds (solid black). The dotted line shows the present outline of the surface. The complex structure of the underlying rock and the rock of the highlands is well shown. (After Barrell.)

In Virginia and North Carolina coal conditions prevailed, but, with the exception of these and the abundant footprints of the Connecticut valley, fossils are rare. Fish and plant remains in thin beds are, however, occasionally found. Since no marine fossils have been discovered in any of the Triassic deposits of the east, the exact age of these deposits is somewhat in doubt, but the evidence points to the Upper Triassic as the time at which they were laid down. This formation is known as the Newark because of its development near the city of that name in New Jersey.

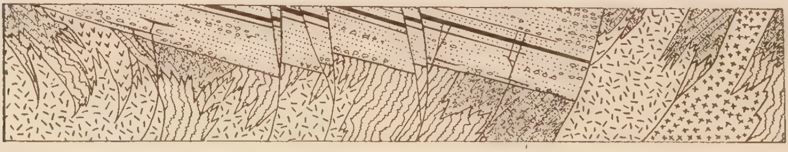


FIG. 483. — Section across the Connecticut valley, showing the same region as in Fig. 482 after faulting had occurred, and after erosion had worn the region to a peneplain. (After Barrell.)

During the deposition of these sediments lava flows of considerable extent and thickness were poured out; dikes and sills were intruded; and in a few places volcanoes were in eruption. The evidence of this igneous activity is especially well shown in the Connecticut valley (Fig. 482), where in certain localities there are three distinct lava flows. The lava forming the Palisades of the Hudson (Fig. 323, p. 326), which varies in thickness from 300 to 850 feet and stretches for 70 miles from north to south, is an intrusion (Fig. 322, p. 326). The faulting and subsequent erosion (Fig. 483) of the Triassic sediments and lavas of Massachusetts, Connecticut, and New Jersey have resulted in hills and mountains of (for these regions) unusual shape.

Western Interior. — In the western interior of North America (map, Fig. 480), the deposits are also for the most part red and, as a rule, devoid of fossils. Some of the sediments were deposited in fresh-water lakes, others in salt-water lakes, and some are probably of eolian origin.

Pacific Coast. — In the early part of the period, the Pacific coast line, with the exception of a comparatively narrow bay that stretched east from California to Wyoming, was probably farther west than now. Later in the period the sea spread over the land until it covered a large area in Alaska, Canada, British Columbia, Washington, Oregon, Nevada, and California, and smaller areas in Mexico. The fossils from the Triassic deposits of the west are in many cases very abundant.

Triassic in Other Continents. — Triassic rocks have a wide distribution in Europe, where both marine and continental deposits occur; the marine being, in general, in the south of Europe and the continental in the northern and central portions. The Triassic in Germany has a threefold division (hence the name Triassic). The lowest consists of deposits which were laid down in fresh and salt lakes, not unlike those of the Triassic of the western interior of North America, and to some extent are of eolian origin, as the dune structure of some of the sandstone shows. Sun cracks, raindrop impressions, and tracks of animals also occur. The relation between the fertility or barrenness of a soil and the rock from which it was derived is well illustrated by this formation in Germany. Since the rocks are composed of quartz sand containing little plant food, the region underlain by them is not cultivated, but has been allowed to remain forested, and hence this formation has been called the "forest formation."

During the Middle Triassic (Muschelkalk) an inland sea connected with the ocean spread over a large part of the area of the earlier formation. This sea was later shut off from the ocean and soon became a salt lake, as the deposits of gypsum and salt show. In the Upper Triassic (Keuper), marine beds, thin coal seams, gypsum and salt deposits, and in the last stage (Rhætic) marine deposits again show a few of the fluctuations of the period.

JURASSIC

Atlantic and Gulf Coasts. — In eastern North America the emergence of the continent seems to have continued from the Triassic, no trace of marine sediments being known except in Mexico where the Gulf of Mexico extended west of its present position. Probably near the close of the Triassic the continent was warped in such a way that the Triassic sandstones and shales of the Connecticut valley were tilted to the east, and those of New Jersey and farther south to the west. The Jurassic, like the Triassic, appears to have been a period of continued erosion in the eastern half of the continent.

FIG. 484. — Map showing the probable outline of North America during a portion of the Upper Jurassic. (Modified after Schuchert.)

Western Interior. — No early Jurassic rocks are known with certainty to occur in the western interior, but later in the period an arm of the sea of great width extended south (Fig. 484) from Alaska to Wyoming, Utah, and the Black Hills of South Dakota. The prevalence of sandstones, with only occasional limestone beds, shows that the sea was a shallow one. Since the fossils of some of the beds are of marine species, closely resembling those of Siberia rather than those of California of the same age, we must suppose that a mediterranean sea was connected at the north with the ocean, and that a long land barrier separated it from the Pacific. After a comparatively short existence this great bay was drained by elevation of the land; and its site was covered in the southern portion by a widespread, continental formation (Morrison) which contains skeletons of dinosaurs and other reptiles and a few mammalian remains. Because of the absence of marine fossils, it is not yet certain whether these beds are late Jurassic or early Cretaceous, or whether the lower portions belong to the earlier period and the upper to the later.

Mountain Forming in the West. — In the west, where the Sierra Nevada Mountains now stand, Jurassic sediments derived from extensive lands on the east had been accumulating in a great subsiding trough (geosyncline), until they had attained a maximum thickness of five or six thousand feet. The sediments deposited in this trough, including Triassic, Jurassic, and Paleozoic, attained the enormous thickness of nearly 25,000 feet. Near the close of the period, this huge accumulation of sediments began to yield to great lateral compression and was folded and upheaved into the first Sierra Nevada Mountains, which perhaps rivaled in height any in existence to-day; they may, however, have been eroded almost as rapidly as they rose and therefore never have reached a great elevation. During the folding great quantities of igneous rocks, especially granites, were forced into the folded sediments, forming upon cooling batholiths and stocks. The muds and sands in the neighborhood of the intrusions were also changed to schists and other metamorphic rocks; and even at a distance shales were metamorphosed to slates. At about the same time, the Coast Ranges, the Cascades, and farther north the Klamath Mountains began their growth. It should not be inferred from the above that the present height of the Sierra Nevadas was the result of these movements: the Sierra Nevadas of to-day, as will be explained later, are the result of a great fault on the east, which occurred at a much more recent date.

Jurassic of Other Continents. — The greater portion of Europe and Asia was above the sea during the earlier part of the period, but a progressive submergence soon began, culminating in the Upper Jurassic, at which time the two continents were traversed by straits and seas which cut them into a number of large and small islands. The submergence of central and northern Russia is of especial interest, since in this basin was developed a peculiar fauna which spread into the great mediterranean sea of the western interior of North America. An arm of the sea covering the site of the Himalayas separated India from northern Asia. This Upper Jurassic submergence in Europe and Asia was one of the greatest in all the recorded geological history of these continents.

LOWER CRETACEOUS (COMANCHEAN)

Atlantic and Gulf Coasts. — No marine deposits of the Lower Cretaceous (Fig. 485) have been found on the Atlantic coast, but a belt of continental sediments, stretching from Marthas Vineyard island to Georgia (the Potomac group), occurs, which seldom attains a thickness of more than 600 feet. The lesson which these deposits teach of the physical condition at, and immediately preceding, the time of their formation is interesting. They show that at the close of the Jurassic the eastern portion of the continent had been reduced to a comparatively level plain over wide areas, the surface of which was covered deeply with weathered rock, resulting

FIG. 485. — Map showing the probable outline of North America during a portion of the Lower Cretaceous. Continental deposits are shown in solid black. (Modified after Schuchert.)

from the decay of the underlying formations, which the slow-moving streams of that time were unable to transport. At the beginning of the Lower Cretaceous, however, the Piedmont and Appalachian regions were raised, perhaps along the axis of the Appalachian tract, while the land nearer the coast was but little disturbed, either remaining comparatively level or being depressed into long troughs, somewhat similar to those of the Triassic. Under these new conditions, the streams in the higher regions began again to erode. On account of the abundance of loose, weathered material, the streams in their courses to the sea soon had all the sediment they could carry and as soon as a lower gradient was reached dropped their loads. This resulted in the formation of deltas, flood plains, marshes, and shallow lakes. The deposits formed in this way were gravels, composed of the quartz of quartz veins and quartzites, clay from the decayed feldspar, shales, and slates, and arkose in the immediate vicinity of feldspar-bearing rocks.

The most striking feature of the Lower Cretaceous geography is the expansion of the Gulf of Mexico towards the west and northwest and the deep subsidence of its floor, upon which were deposited a great thickness of limestones. Large areas in Mexico, Texas, and New Mexico were covered at this time. In this sea the Ouachita Mountains stood out as a promontory, as is shown by the ancient shore line which has been traced around their foot. The sediments have a thickness of 5000 feet on the Rio Grande and are even thicker in Mexico. At the base of this marine formation is one which is in part a littoral deposit but is mostly marine (Trinity).

Western Interior. — In the western interior non-marine formations, sometimes including coal beds, occur (Morrison which may be Jurassic, Kootenai, Cloverly, Lakota, Fuson).

Pacific Coast. — On the Pacific coast the conditions were very favorable for erosion, because of the newly raised Sierra Nevadas which were being rapidly cut away, the material derived from them forming a thick deposit in the Sacramento valley. In addition to this area, other narrow strips were submerged east of the present coast of British Columbia and Alaska, during portions of the period.

Lower Cretaceous of Other Continents. — In Europe, as in North America, the Lower Cretaceous formations are largely of continental origin and are not as widespread as those of the Upper Cretaceous. In general, it can be said that important geographical changes occurred in various parts of the earth at the close of the Lower Cretaceous, as are recorded in the unconformities between the Lower and Upper Cretaceous strata and in the difference in their distributions.

Upper Cretaceous (Cretaceous)

The Upper Cretaceous was a period of great subsidence (Fig. 486), no other in the earth's history since the Paleozoic being comparable to it. Not only were portions of the Atlantic and Pacific coasts submerged, but a vast inland sea covered for a time the central portion of North America, from the Gulf of Mexico to the Arctic Ocean (Fig. 486), separating it into two land masses.

Fig. 486. — Map showing the probable outline of North America during a portion of the Upper Cretaceous. The inland or epicontinental seas were widespread. Continental deposits are shown in solid black. (Modified after Schuchert.)

Atlantic and Gulf Coasts. — The sea spread over the coastal plains of the Atlantic and Gulf states, and strata composed of sands, clays, chalk, and "green sands" (glauconite) were accumulated. The map (Fig. 486) shows the supposed distribution better than a written description. At this time the eastern half of the continent was probably a comparatively flat plain (Kittatinny peneplain) to which it had been reduced during the long ages of the earlier Mesozoic, notwithstanding occasional warpings. Across this plain the Potomac, Susquehanna, and Delaware rivers meandered, probably in very much the same courses as to-day.

Pacific Coast. — On the Pacific coast Upper Cretaceous sediments occur in California and northward at points as far distant as Alaska, where they are sometimes conformable and sometimes unconformable. Usually they are not thick, but in one locality (California), at least, they apparently reach the great thickness of 25,000 feet.

Western Interior. — The geography of the western interior can be roughly divided into (1) an epoch when the sea was excluded, and beds, mainly of non-marine (Dakota) sediments, were laid down; (2) an epoch of pronounced extension of the sea during which a great thickness of marine sediments (Colorado and Montana) accumulated; and (3) an epoch during which the land was so low that slight oscillations produced conditions which resulted in the formation of bodies of salt, brackish, or fresh water (Laramie).

(1) The sediments of the first epoch (Dakota) probably covered an area 2000 miles long by 1000 miles wide, which stretched from Canada on the north into Texas on the south, and from Minnesota and Iowa on the east to beyond the present site of the Rocky Mountains on the west. The formation is largely sandstone, though it contains much conglomerate and clay, and some lignite. At this time marshes and lagoons existed near the shores, while inland sluggish streams were depositing fine sediment over the bottom. The presence of brackish water fossils in beds of this age in Kansas indicates marine conditions at certain times, or at least a low shore on which fresh and salt water were mingled. The porous beds thus formed are now the great water-bearing strata of the Great Plains, the water of these porous sandstones being derived from the rains which fall upon and the streams which flow over their upturned edges in the mountainous regions. Although of such wide extent, the Dakota sandstones have a fairly uniform thickness of only 200 to 300 feet.

(2) This epoch (Dakota) was followed by one of extensive submergence which resulted in the formation of a great sea (Colorado), stretching from the Gulf of Mexico to the Arctic Ocean and covering the Great Plains of Canada and the United States and the site of the Rocky Mountains, with the possible exception of some large and small islands. As the sea encroached upon the land, muds were first deposited, but as it deepened and widened the waters became clearer, and chalk and limestone were laid down locally, while in the extensive bordering swamps peat accumulated to form important beds of coal which are best developed in Wyoming and Utah. This

larger sea gave place later to a somewhat more constricted one (Montana), along the edges of which the conditions were favorable for coal formation. This is shown by thick coal beds of this time in Montana, Wyoming, California, Utah, and New Mexico. It is probable that neither of these seas was of great depth.

(3) The closing epoch of the western interior was the Laramie. The evidence points to a land so low that a slight oscillation either raised or submerged it. When the latter occurred, the sea overspread the land, and marine sediments were deposited; as the sea was filled in by sediments or was partially drained by elevation, swamps and marshes were formed and peat accumulated in sufficient quantities to form later some workable beds of coal. There is probably as much coal in the Cretaceous formations of the west as in the Carboniferous of the eastern United States, though usually of a poorer quality.

There is some disagreement as to where the line between the latest Cretaceous (Laramie) and the earliest Tertiary (Eocene) should be drawn. A formation (Lance) in Wyoming, containing dinosaurian remains and other typical Mesozoic animals but with plants that have a Tertiary aspect, is separated from the Laramie below by an unconformity involving, it is thought, the removal of over 20,000 feet of strata. This formation is placed by some in the Tertiary, although others believe that it should be included in the Mesozoic.

The maximum thickness of the Upper Cretaceous in the western interior is about 24,000 feet, making it one of the great systems of the earth.

Upper Cretaceous of Other Continents. — Not only was the Upper Cretaceous a period of great submergence in North America, but in other continents as well. Large tracts of Europe were beneath the sea at this time.

Limestones were deposited in southern Europe, and chalk (p. 523), to a thickness of several hundred feet, accumulated in France and England; the latter has, however, little development elsewhere on the continent. In Asia the land area was much smaller than now, the Himalaya region, as well as large tracts in India and elsewhere, being covered with water. Australia and South America show a similar extension of the seas. The summits of much of the eastern Andes of South America, to a height of 14,000 feet or more, are formed of Upper Cretaceous beds.

The Cretaceous Peneplain. — Before the close of the era, not only North America but Europe and Asia appear to have been reduced by erosion to low, monotonous plains upon which few, if any, elevations of great height remained (p. 114). This being the case, the era as a whole must have been one of great quiet, during which crustal movements were uncommon. One should remember, however, that at the close of the Triassic the faulting and elevation of the sandstones and shales of that period occurred; that at the close of the Jurassic, the Sierra Nevadas were raised, but that before the end of the Upper Cretaceous even these elevations had for the most part disappeared. The Appalachians were largely worn down to base level, and the Laurentian region of Canada was a comparatively flat plain. Under these conditions the streams of that time flowed in meandering courses to the ocean, and the climate was probably uniform, warm, and humid.

Mountain-making Movements at the Close of the Mesozoic. — During the closing stages of the Upper Cretaceous, great crustal disturbances began which resulted in the formation of mountain ranges from Alaska to the southern tip of South America. These movements, following the long period of quiet just described, were not sudden, but were anticipated by upwarping in Colorado, Wyoming, and other places, as the presence of more abundant coarse sediments indicates. The great Rocky Mountains of Canada and the United States had their birth at this time, but not their full growth until later. The structure of these mountains is in marked contrast to that of the Appalachians, whose elevation was the result of great lateral movements which folded and crowded together the strata. Although horizontal compression was important in the formation of the Rocky Mountains, the result of the vertical movements is much more conspicuous (p. 364). The growth was also assisted by faulting. In Utah the Wasatch and Uinta mountains and in British Columbia the Gold Range were also raised.

That the deformation did not take place previous to the Laramie is proved by the fact that the strata of this stage and those of greater age are folded with equal intensity, while the overlying Tertiary rocks are less disturbed, showing that the deformation took place before the deposition of the latter. In some areas, however, the lowest Eocene (Fort Union and Wasatch) show as steep dips and were apparently as much disturbed as the underlying Cretaceous, indicating later deformation. These disturbances were accompanied by volcanic eruptions and intrusions of lava. The laccoliths forming the Henry Mountains of Utah were elevated by lava which was forced into the strata at this time. At this time, too, a large part of the continent of North America was affected by movements of greater or less strength, so that at the close of the era, dry land extended from the Sierra Nevadas on the west to the "Fall Line" on the east.

With the formation of the Rocky Mountains, the fourth great range of the North American continent came into existence; the Taconics being formed at the close of the Ordovician, the Appalachians at the close of the Paleozoic, and the Sierra Nevadas at the close of the Jurassic.

Duration of the Mesozoic. — Many facts point to a great duration for this era. (1) The erosion of an immense thickness of rocks from the Appalachian Mountains and the reduction of the continent to a peneplain was accomplished during the era and must have taken an almost inconceivable length of time. (2) The first Sierra Nevada Mountains, although formed in the latter half of the era, were not only raised — possibly to a great height — but were also, later, worn down to a peneplain. (3) During the Upper Cretaceous alone, 24,000 feet of sediments — almost five miles — were deposited, being worn from the land and carried little by little to the seas by the streams. (4) The evolution in the animal and plant life of the era is very striking, from the standpoint of both form and structure. It does not seem possible that, under the conditions existing at that time as we understand them, these changes could have been brought about rapidly.

No matter upon what basis the estimate is made; whether the time necessary for the erosion of thousands of feet of strata, or that required for the deposition of great piles of sediment, the length of the era must have been enormous. An estimate of 9,000,000 years has been suggested, but should be taken merely as an approximation. It may be too large, or several millions of years too short.

REFERENCES FOR PALEOGEOGRAPHY

Barrel, J., — *Rhythms and Measures of Geological Time:* Bull. Geol. Soc. America, Vol. XXVII, 1917, p. 752.

Chamberlin and Salisbury, — *Geology*, Vol. 3, pp. 1–38; 59–79; 106–130; 137–172.

Schuchert, Chas., — *Paleogeography of North America:* Bull. Geol. Soc. America, Vol. 20, 1910, pp. 427–606.

Schuchert, Chas., — *Climates of Geologic Time:* Carnegie Institution of Washington, Pub. 192, 1914, pp. 280–284.

LIFE OF THE MESOZOIC

In the early days of the study of geology it was believed by many that life ceased to exist at the close of the Paleozoic and was re-created at the beginning of the Mesozoic. This belief was based upon the great dissimilarity of the life of the two eras and upon the apparent absence of fossils in the intermediate strata. As a more careful study of these rocks was made, and new exposures were discovered, fossils were found which, though rare, proved that the life was in many respects transitional. The change in vegetation between the two eras was not cataclysmic, as was formerly supposed, though "it was rapid or almost sudden." (D. H. Scott.) The animal life suffered even more than the plant, very few of the Paleozoic genera surviving in the following era. The transition, in other words, apparently took place with great rapidity and affected all classes of life. If a change in the character of the rocks is made a basis for separation, it is found that although great unconformities occur, yet in many places it does not seem possible to tell where the dividing line should be drawn. For example, in America (Kansas and Wyoming) between horizons yielding Permian fossils and those yielding Mesozoic there are "at least one thousand feet of continuous, conformable, uninterrupted, and homogeneous deposits of red sandstone which may belong to one period or to both," and in Europe the Permian in many places merges into the Mesozoic (Triassic) so insensibly that it is impossible to state where one ends and the other begins.

Comparison of the Life of the Paleozoic and the Mesozoic. — The dominant plants and animals of the Paleozoic disappeared, for the most part, with the Permian. The lepidodendrons, sigillarias with the exception of a few stragglers, Calamites, Cordaites, sphenophylls, and a number of important genera of ferns had vanished; and their places were taken by a flora of very different character, so that the forests of this era were very unlike those of the preceding in general appearance.

With the close of the Paleozoic, the abundant corals of that era had disappeared and were replaced by a new type, differing (p. 524) both in structure and appearance.

No cystoids or blastoids survived. The crinoids are, with the exception of two genera, of a type quite different from those of the Paleozoic. The race had reached its zenith and its decline had begun, though now and then a species made its appearance which by its local abundance seemed, for a time, to give promise of regaining the former importance of the race. Sea urchins, which for the millions of years of the Paleozoic had remained in a subordinate position, were replaced by forms of modern structure and occupied, to some degree, the place vacated by the crinoids, cystoids, and blastoids.

The brachiopods of the Paleozoic were, as far as external appearance is concerned, of two classes; those with long hinge lines, giving them a square-shouldered look, and those with short hinge lines and sloping shoulders. Of these, the square-shouldered and most characteristic type soon disappeared, and only a comparatively few genera of the sloping-shouldered type survived. The brachiopods, as was true of so many other classes, after attaining considerable importance gave way to other classes of animals. In this case, as they decreased in abundance, the pelecypods and gastropods increased. The comparatively simple-sutured cephalopods of the Paleozoic, such as the Orthoceras and the angled goniatite (p. 459), were quite suddenly replaced by an abundance of cephalopods with complicated sutures. The Orthoceras, which lived throughout the whole of the Paleozoic, had a few survivors in the Triassic, but these soon became extinct.

The fishes of the Triassic resemble those of the Permian in most particulars, but many of the Permian genera are wanting. The Age of Amphibians passed with the Permian; and although the Stegocephalia (p. 485) lived on into the Triassic, they disappeared before its close; and the insignificant frogs and salamanders of the present are the sole representatives of that once varied and conspicuous race.

The cause of the revolution in life at the close of the Paleozoic, as has been seen, must be found in the very different physical conditions which were present at this time, since not one or two but many orders of animals and plants either became extinct or were profoundly affected. The formation of great mountain ranges, the withdrawal of epicontinental seas in America, Europe, and elsewhere, must have produced a climate markedly different from that of the Carboniferous, since the ocean currents, with their great stores of heat, would be forced to take courses different from those which they formerly held. Moreover, the circulation of the air would be affected by the high mountain ranges. Besides these more evident causes, it is possible that a radical change in climate resulted from the withdrawal of carbon dioxide during the Carboniferous, and that this, combined with the above-mentioned and other physical changes, caused the extinction of those species which, because of their lack of variability, could not adapt themselves to the new conditions.

Plan of Study. — For the sake of continuity in the study of the various groups of animals and plants described, the life of the four periods of the Mesozoic will not be studied separately, but the periods in which the genera and species occur will often be referred to.

INVERTEBRATES

Chalk. — Chalk is composed largely of the remains of Foraminifera. Although these unicellular organisms have been found in Paleozoic strata, being abundant in the Lower Carboniferous (Mississippian), it was not until the Jurassic that they attained a great development. Although conditions were very favorable for their increase in the Jurassic of Europe (but not of America) and still more so in the Cretaceous, they were even more important as rock builders in the Tertiary.

The best known chalk deposits are those of which the cliffs of Dover, England, and Dieppe, France, form a part; and because of their conspicuous character, the name Cretaceous — Age of Chalk — was given to the period in which they occur. In the United States also, Cretaceous chalk is extensive. Chalk and chalky limestone many hundred feet in thickness are found in the Lower Cretaceous series of Texas; and another deposit in the Upper Cretaceous extends from Texas northward through the Great Plains region, in Kansas, Colorado, and Nebraska. However, this name is not altogether appropriate, since by no means all the rocks of that period are composed of chalk. It seems probable that the chalk of the Cretaceous was not deposited in seas of great depth as is true of the Globigerina (chalk) ooze of to-day, which in portions of the ocean is being laid down at a depth of 12,000 feet or more, but that the water was only moderately deep. The occurrence in the chalk of certain mollusks which do not seem to be of deep-sea species indicates this. Therefore, there is little reason to believe that the great chalk beds of the Cretaceous were deposited at depths of thousands of feet, and that the ocean bottom was later raised to form dry land. An explanation for the purity of the chalk, if deposited in comparatively shallow water, is to be found in the conditions existing at the time. As a result of the low relief of the land with its thick covering of vegetation, there was little erosion, and the scanty sediments were laid down but a short distance from the shore. Consequently, the Foraminifera which throve in great abundance near the shores as well as in the waters of the deep seas, as they do to-day, were not upon their death covered with clastic sediments, but in the course of time built up thick deposits of lime, composed largely of their own remains. The genera and species of Foraminifera have generally, as might be expected from their low organization, a long range in time: some of the genera which occur in the Paleozoic are still living.

Flint nodules, varying in shape and ranging in size from that of a walnut to two feet in length, are of common occurrence in certain portions of many chalk beds. They are composed largely of siliceous protozoa (Radiolaria), sponge spicules, and silica that has no organic form. These flint nodules were probably formed by concretionary action, the silica scattered rather uniformly throughout the deposits being brought together to form masses of varying size.

Sponges. — Sponges appeared in the Triassic of Europe in small numbers and became so numerous in certain localities during the Jurassic as to form thick strata with their remains. They were still more abundant in the Cretaceous of Europe, though not common in America.

Corals. — The Paleozoic corals (Tetracoralla) did not immediately give place to the modern type (Hexacoralla, Fig. 487 *A*, *B*), but a few lingered for a short time in the Triassic. Before the close of that period, the new type (Hexacoralla) became so thoroughly established as to build coral reefs where conditions were favorable. It was not, however, until the Jurassic that extensive reefs were formed by their remains. The general appearance of the Cretaceous corals is not unlike that of the corals of to-day.

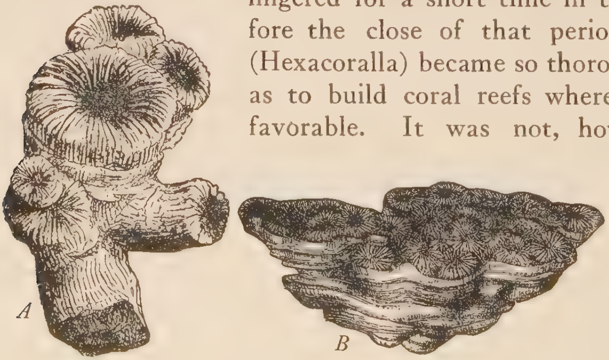


FIG. 487. — Mesozoic corals: *A*, *Thecosmilia trichotoma* (Triassic and Jurassic); *B*, *Thamnastræa prolifera* (Jurassic).

Crinoids. — This class (Fig. 488 *A*, *B*) was rare both near the beginning and with some exceptions (Uintacrinus of the Niobrara Chalk of Kansas), near the close of the Mesozoic, but became abundant, though not diversified, in the Jurassic, at which time the crinoids attained their greatest size and beauty. The stem of one has been traced seventy feet without reaching either end. The "head" in some individuals (Fig. 488 *A*) is as large as a feather duster and similar to it in appearance. The genus to which these large specimens belong (Pentacrinus) is still found in the West Indian seas. In America the class appears to have been rare throughout the era.

Although the structure of the Mesozoic and Tertiary crinoids differs markedly from that of the Paleozoic, perhaps the most conspicuous external difference lies in the great development and subdivision of the arms and the relatively small body (calyx) of the later type. All Paleozoic crinoids were attached to the sea bottom by stems, and this was also true of the great majority of the Jurassic genera, but a few free-swimming forms began then and have continued to the present. In these unattached forms, the animal begins its existence fixed to the bottom by a stem, as did its ancestors, but later becomes free.

Fig. 488. — Mesozoic crinoids: *A, Pentacrinus fossilis; B, Apiocrinus parkinsoni* (without arms).

Sea Urchins (Echinoids). — A new type of sea urchin (Fig. 489 *A–C*), which had a few forerunners in the later Paleozoic, soon entirely replaced the older type. One marked difference between the two groups lies in the number of rows of plates forming the "shell," which was variable in the old, but in the new was constant. Early in the era, a fivefold symmetry (Fig. 489 *A*) was the rule, but later a twofold or bilateral symmetry characterized the greater number of species. Sea urchins with club-shaped spines (Fig. 489 *A*) were abundant in the Jurassic and Cretaceous. Inconspicuous, and for the most part rare throughout the ages of the Paleozoic, sea urchins had a rapid development early in the Mesozoic, became abundant in the Jurassic and Cretaceous, assuming the place formerly held by the crinoids, and finally culminated in the Tertiary.

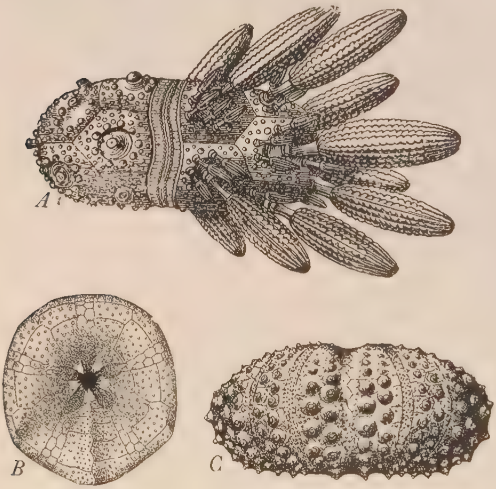


FIG. 489. — Mesozoic echinoderms: *A*, *Cidaris coronata* (Jurassic); *B*, *Cassidulus subconicus* (Upper Cretaceous); *C*, *Diplopodia texanum* (Lower Cretaceous).

Starfish. — Starfish are not a conspicuous race in the Mesozoic.

Brachiopods. — Aside from the abundance of a few genera at different times in the Triassic and Jurassic, there is little of interest in this class in the Mesozoic. Most of the species (Fig. 490 *A–D*) belong to the genera that are living in the seas of to-day and are almost exclusively of three families. A few of the Paleozoic long-hinged type (Spiriferina, etc.) survived for a short time, but were inconspicuous. After their long period of ascendancy in the Paleozoic, brachiopods became unimportant and have remained in a subordinate position ever since.

Pelecypods. — Almost in proportion as the brachiopods declined the pelecypods (Fig. 491 *A–J*) increased, both in numbers and variety. This rapid development is shown in the Triassic, where only about one fourth were of Paleozoic genera. In the Jurassic, the oyster tribe is conspicuous and is represented not only by the true oyster but by others that, although belonging to the same order, have a different external appearance (Gryphæa, Fig. 491 *C*, Exogyra, etc.) and are much more characteristic. In the Jurassic and still more in the Cretaceous, a number of pelecypod genera appear which depart radically from the typical forms in which the

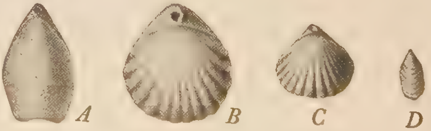


FIG. 490. — Mesozoic brachiopods: *A*, *Terabratula humboldtensis* (Triassic); *B*, *Rhynchonella æquiplicata* (Triassic); *C*, *Rhynchonella gnathophora* (Jurassic); *D*, *Lingula brevirostra* (Jurassic).

two valves are alike. In some of these (Diceras, Fig. 491 *F*) each valve is horn-shaped; in others (Requienia, Fig. 491 *J*) one valve is long and spirally twisted and the other flat, with a low spiral; in others (Radiolites, Fig. 491 *G*) one valve has the appearance of a cup coral and the other is flat with prolongations extending into the

FIG. 491. — Mesozoic pelecypods: *A*, *Halobia* (*Daonella*) *lommeli* (Triassic); *B*, *Trigonia clavellata* (Jurassic); *C*, *Gryphæa arcuata* (Jurassic); *D*, *Inoceramus vanuxemi* (Upper Cretaceous); *E*, *Aucella pioche* (Lower Cretaceous); *F*, *Diceras arietinum* (Jurassic); *G*, *Radiolites cornu-pastoris* (Upper Cretaceous); *H*, *Eumicrotis curta* (Jurassic); *I*, *Camptonectes bellistriatus* (Jurassic); *J*, *Requienia patagiata* (Lower Cretaceous). *C*, *F*, *G*, and *J* present forms very unlike the typical pelecypod.

horn-shaped valve. These irregular, unsymmetrical bivalves are usually firmly attached by one valve, their irregular development being due, to some degree, probably largely, to this fact. It is interesting to note that these extraordinary forms appear contemporaneously with the extravagantly modified cephalopods. A characteristic Cretaceous genus is Inoceramus (Fig. 491 *D*), also found in Jurassic deposits.

Gastropods. — The Mesozoic gastropods (Fig. 492 *A*, *B*) were, as a whole, less simple than those of the Paleozoic, although many of the older type, in which the mouth of the shell is a complete ring, lived on. In one branch, a tube was developed through which the waste waters of the body were carried and emptied some distance from the opening into which the fresh waters entered, a structure the advantage of which is obvious. Forms of this type were lacking in the Paleozoic, but became common before the close of the Mesozoic. Towards the close of the era many of the genera which reached their highest development in the Tertiary and recent times appeared.

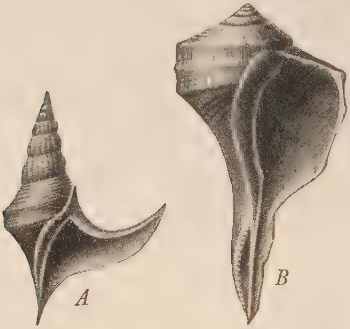


FIG. 492. — Mesozoic gastropods: *A*, *Anchura americana* (Cretaceous); *B*, *Pyropsis bairdi* (Cretaceous).

Cephalopods. — The Paleozoic types of cephalopods (Fig. 407 *A–D*) are represented in the Triassic strata by orthoceratites and goniatites and occur with the fringe-sutured ceratites (Fig. 493 *I*) and the complex-sutured ammonites (Fig. 493 *A*), but soon disappear.

Ammonites. — Ammonites "developed with wonderful rapidity from the first rare members [in the Upper Silurian or Devonian] into numerous families, hundreds of genera, and thousands of species, reaching their acme in the Jurassic." "In the Cretaceous they gradually declined, dropping off one at a time, until all are gone before the end." (J. Perrin Smith.) In numbers, diversity of form, and ornamentation, ammonites are remarkable. Especially towards the end of the race (in the Upper Cretaceous) unusual forms appeared. At this time — and occasionally in the Triassic and Jurassic — many began to uncoil; some were coiled during the early part of their life, but as they approached old age became less coiled (Scaphites, Fig. 493 *L*); others formed open coils (Crioceras, Fig. 494 *A*); some

FIG. 493. — Mesozoic cephalopods: *A*, *Tropites subbullatus* (Triassic), side and front views; *B*, Development of sutures in *Tropites*; *C*, *Lytoceras fimbriatum* (Jurassic); *D*, *Perisphinctes achilles* (Jurassic); *E*, *F*, *Meekoceras gracilitatis* (Lower Triassic), front and side views; *G*, *Sagenites herbichi* (Upper Triassic); *H*, *Turrilites catenatus* (Cretaceous); *I*, *Ceratites nodosus* (Triassic); *J*, *Baculites*, showing the complexity of the sutures (one segment is shaded to emphasize this); *K*, *Cardioceras cordatum* (Jurassic), side and front views; *L*, *Scaphites nodosus* (Cretaceous).

were turreted (Turrilites, Fig. 493 *H*); one common form (Baculites, Fig. 493 *J*) became straight like the Orthoceras; others assumed forms which seem to have been entirely a matter of accident, as is shown especially well in a specimen from Japan (*Nipponites mirabilis*, Fig. 494 *C*). Many suggestions have been made to account for the "death contortions" of the ammonites, but none is satisfactory. The one most in favor is that they mark the senility of the race.

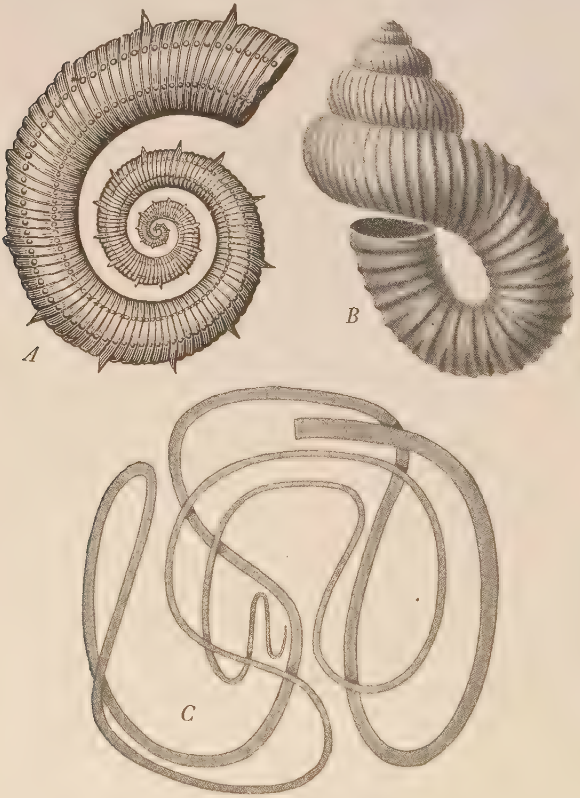


Fig. 494.—Cretaceous ammonites: *A*, *Crioceras*; *B*, *Nostoceras stantoni* (Cretaceous). In this specimen the death of the animal was probably caused by its own growth, as the edge of the living chamber is almost in contact with the lowest whorl of the spiral; *C*, Restoration of *Nipponites*, a remarkable genus from Japan.

The descent of ammonites from goniatites (p. 459) is shown in two ways: (1) by comparing specimens from successively older formations and noting the progressive changes, and (2) by studying the oldest and youngest portions of the shell of an individual (Fig. 493 *B*). In these shells every stage in the growth of the individual is preserved, so that if the shell of a full-grown ammonite is separated along its septa from the apex to the living chamber and its sutures studied, it is found that they increase in complexity—the first suture or two made by the animal when young being simple, like those of the Silurian nautilus; then follow a few like those of the Devonian goniatites (Fig. 434 *A*, *B*); the complicated ammonite sutures beginning when the whorl is only two or three millimeters in diameter. In other words, each individual ammonite recapitulates the history of its race. It is consequently possible by studying a well-preserved individual to tell what its genealogical tree was. In no other animal can the evolution of the race be so well studied. It should be borne in mind, however, that the record of some of the stages of development is often omitted by "acceleration."

Since many of the species had a very short life, they are especially important in showing that widely separated strata are of the same age. It should be remembered, in this connection, that ammonites were free-swimming or crawling animals, and also that upon their death the gases of putrefication caused them to float. They were consequently moved, either by their own volition or by the ocean currents after their death, over wide areas, and hence are excellent "index fossils." The ammonites contributed largely to the Jurassic limestones, but of all this great horde of shelled cephalopods, the simple-sutured nautilus alone survived the Mesozoic.

Naked Cephalopods (*Belemnites*). — In Jurassic deposits straight, cigar-shaped fossils (Fig. 495) are sometimes found in great abundance. These belemnites are usually 3 to 5 inches in length, although some specimens several feet long have been found. Ink bags are associated in some specimens, showing that their possessors darkened the water to escape their enemies, as do the squids of the present. These are the internal shells of naked cephalopods which resembled the squids of to-day in general appearance. This class is first known from the Triassic, but once started, the race rapidly increased, culminating in the Jurassic and declining rapidly in the Cretaceous. Only one surviving genus (Spirula) is living to-day. The solid internal shells of the belemnites constitute a considerable part of some Jurassic limestones.

FIG. 495. — Restoration of a *Belemnite*. The solid, cigar-shaped "guard" (lower end) is a common fossil in the Jurassic and Cretaceous. Next above the "guard" is the phragmocone, and above this the proöstracum.

Crustaceans. — Crustaceans (Fig. 496 *A*, *B*) of a very modern appearance took the place of the trilobites and eurypterids. In America few fossils of this group have been found, but in the Jurassic lithographic limestone of Bavaria many beautifully preserved specimens have been collected. It is possible that this class was as abundant in America as in Europe, but if so, the conditions for the preservation of the remains were not favorable. Ancestral long-tailed crustaceans of the lobster and shrimp type (Macrura) began in small numbers in the Triassic, and a few survivors of these ancient forms are living in the deep seas of the present. Crabs are, in general, crustaceans of the lobster type in which the tail is abbreviated and turned under the body and the shell widened and otherwise modified (Brachyura). Crabs did not appear until the Jurassic and were derived from the long-tailed series, as numerous specimens intermediate between the two show.

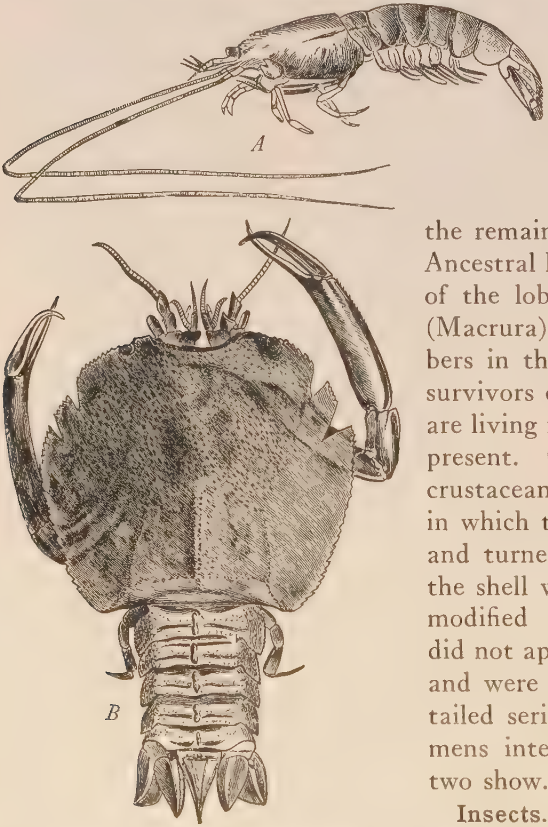


Fig. 496. — Mesozoic crustaceans: *A*, *Penæus meyeri* (Jurassic); *B*, *Eryon propinquus* (Jurassic).

Insects. — Insects are better known from the Jurassic than from any other portion of the era, probably, as in the case of the crustaceans, because the conditions favorable for the preservation of their remains were better than at other times. True cockroaches and beetles are known from the Triassic; and practically all of the groups of to-day were present in the Jurassic, with the exception of those depending upon flowering plants for their food. Crickets, locusts, and cockroaches (Orthoptera), May flies, dragon flies, and caddis flies (Neuroptera) occur. Wood beetles are found associated with driftwood in the Jurassic; and flies (Diptera), plant lice, and aquatic bugs (Hemiptera) are known. The absence of insects depending upon the pollen and nectar of flowers is probably indirect evidence that flowering plants were not yet in existence in the Jurassic.

REFERENCES FOR INVERTEBRATES

CHAMBERLIN AND SALISBURY, — *Geology*, Vol. 3, pp. 48–58; 80–94; 134–136; 186–190.
GRABAU AND SHIMER, — *North American Index Fossils.*
SCOTT, W. B., — *An Introduction to Geology*, pp. 670–673; 684–690; 716–718.
ZITTEL-EASTMAN, — *Textbook of Paleontology*, 2d ed. (for description and bibliography).

FISHES AND AMPHIBIANS

At the beginning of the Mesozoic, less modification in structure is noticeable in this class than in others to be considered, but the changes were by no means inconsiderable.

The shark tribe (Fig. 497 *A*) has had a long and varied history. It began in the Silurian and abounds still in the warm seas of the present. These fish were abundant, both in species and individuals, in the Lower Carboniferous (Mississippian), but during the Permian declined rapidly, almost to extinction. In the early Mesozoic, however, they once more began to increase and were common before its close. The cobblestone-pavement toothed shark lived on and is represented to-day by one genus, the Port Jackson shark (Cestracion). A possible explanation of this curious fluctuation is as follows: in the Carboniferous, being the most powerful animals and having no enemies, they multiplied until their increase was checked by their very numbers. Then the overspecialized forms and those that failed to respond to changed conditions dropped out, leaving the best to survive. These, then, gradually increased to the Middle Tertiary when, through a change in climate, they became again comparatively rare. (Lucas.)

The skates and rays (Fig. 498) are sharks in which the body has been admirably adapted to bottom living and probably should be regarded as "the culminating forms of the specializing, bottom-living sharks of the Mesozoic." (Dean.) The skates of the Mesozoic and Tertiary, without doubt, mimicked the color of the ocean bottom and glided along inconspicuously, just as their living descendants do. The teeth of all skates are simple, crushing, pavement teeth, suited for crushing the shellfish and crustaceans upon which they live. They are first known in the Jurassic and are abundant in the seas of to-day.

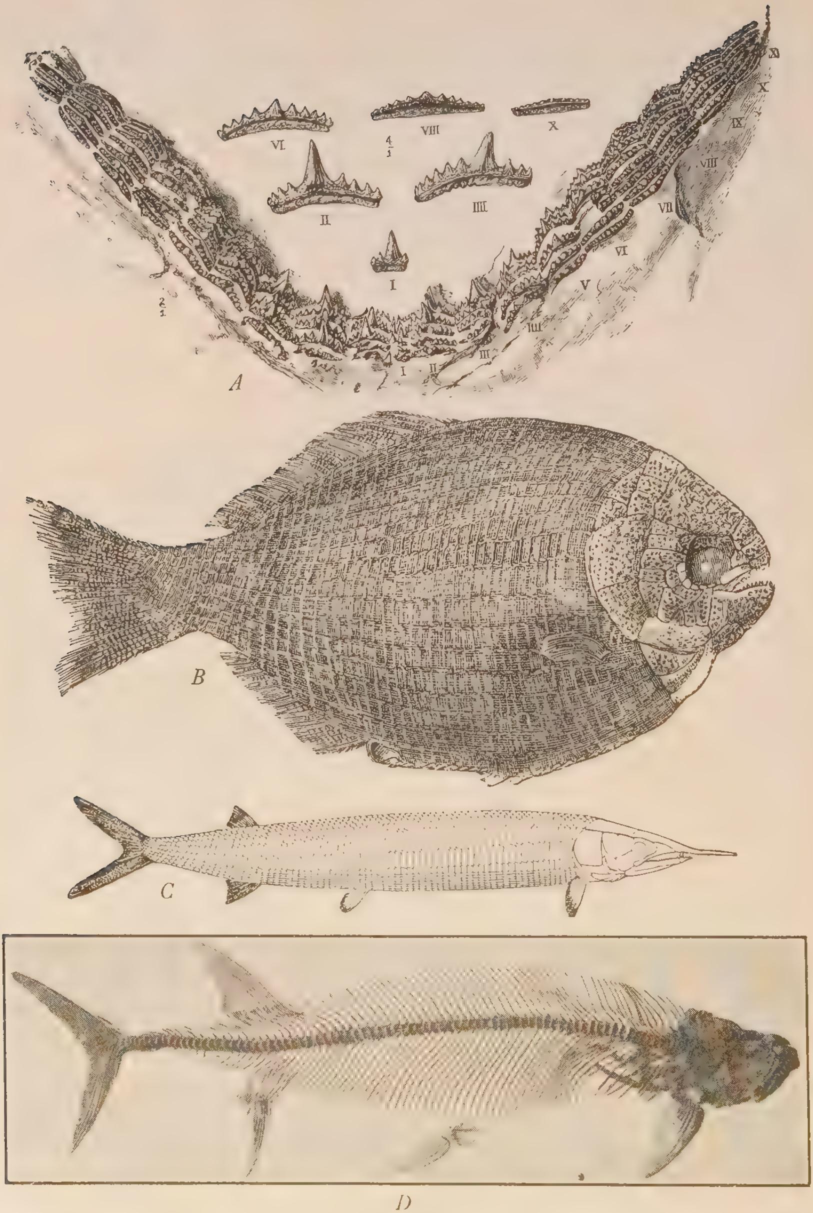


FIG. 497. — *A*, jaw and teeth of the shark, *Synechodus* (Cretaceous); *B*, ganoid fish, *Dapedius* (Triassic); *C*, ganoid fish, *Aspidorhynchus* (Jurassic); *D*, teleost fish, *Portheus* (Cretaceous).

The lungfish almost disappeared from the seas of the Mesozoic, but a few (the best known of which is Ceratodus) have succeeded in living on in small numbers to the present.

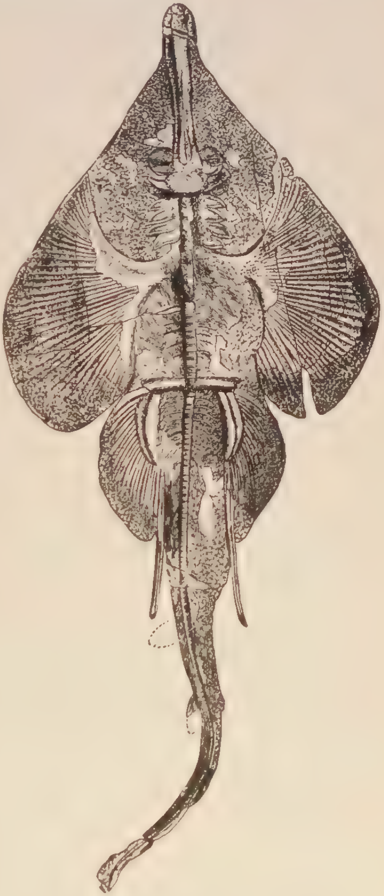


Fig. 498. — An ancestral skate, *Rhinobatus* (Jurassic).

Ganoids (Fig. 497 *B*, *C*) were the common fish of the Triassic and Jurassic. Although they had no bony skeleton, they are well preserved because of their thick, enameled scales which were exceptionally well suited for fossilization. The ganoids are, as a rule, rather small fish and few attained the size of sharks. As the modern fishes with bony skeletons (teleosts) increased during the Cretaceous and Tertiary, the ganoids gradually disappeared until, at present, only a few species are in existence. Two of the commonest living ganoids are the gar pike and the sturgeon, both of which are extremely plentiful in some localities.

The bony fishes (teleosts), descendants of the ganoids, have been found in small numbers in the Lower Jurassic, but probably began in the Triassic. They held a subordinate place, however, until the Cretaceous, when they appeared in great numbers. Among the teleosts of the Cretaceous were herring, cod, salmon, mullet, perch, and catfish. One characteristic Cretaceous type, Portheus (Fig. 497 *D*), should be mentioned. It was a teleost that occasionally attained a length of fifteen feet and was provided with large, flattened, irregular teeth. The suddenness of the appearance of teleosts was due to the fact that, once they were established and able to compete with the fish of that time, there was no hindrance to their migration, and, in a comparatively few years, geologically, they had spread into the seas of the whole world. Most of the ganoids became extinct, either because of their inability to compete with the teleosts in the search for food, or because of climatic and other conditions.

REFERENCES FOR FISHES

Dean, B., — *Fishes, Living and Fossil.*
Eastman, C. R., — Ann. Rept. New Jersey Geol. Surv. for 1904.
Woodward, A. S., — *Vertebrate Palæontology.*
Zittel-Eastman, — *Textbook of Palæontology.*

Amphibians. — The amphibians reached their greatest development in the Permian, but were present in considerable numbers in the Triassic, after which their remains are seldom found. Individuals of this class attained their greatest size in the Triassic, Mastodonsaurus (so-called because of its bulk) having a skull four feet long and probably attaining a length of 15 or 20 feet. Although large for an amphibian, the size is not great as compared with some modern crocodiles. In general appearance, Mastodonsaurus resembled the modern salamander, but it differed in several essential points of structure. Its teeth were of the complicated labyrinthine type (p. 485), and the skull was roofed over with bony plates (Stegocephali). It is possible that bony plates protected the chest, but if so, positive proof is lacking. The Stegocephali became extinct before the close of the Triassic, and thus far with the exception of two specimens of frogs from Wyoming no amphibian remains have been found in Jurassic rocks. The cause of the extinction of this great amphibian order is probably to be found in the highly developed reptiles, large and small, with which they had to compete. A few specimens of salamanders of modern type, differing little in general appearance from the salamander of to-day, though of a different genus, have been found in the Cretaceous. Because of the lack of fossil evidence, the ancestry of the modern amphibians is not known.

Reptiles

Reptiles with Mammalian Characters. — The reptiles with mammalian characters, as far as fossil evidence shows, began, and were represented by many genera in the Permian (p. 490), but, since they apparently attained their greatest development in the Triassic, their discussion has been postponed to this chapter. This group of reptiles is included under the term Theromorpha (Greek, *ther*, beast, and *morphe*, form), because of the strong resemblance, both in teeth and skeleton, to mammals. They are remarkable in possessing not only mammalian characters, but amphibian as well, and occupy a position intermediate between mammals and amphibians. It seems probable that the Theromorpha include the progenitors of the mammals. (Broom, 1911.) One amphibian character is seen in the backbone, the bodies of the vertebræ of which are hollow at both ends (amphicœlous) and, in some cases, are only partly converted into bone. The teeth of certain genera (Cynognathus) are of three kinds as in mammals: incisors, canines, and molars. In some cases the limbs are decidedly mammal-like in structure. Another group of theromorphs have toothless jaws (Figs. 499, 500), covered with horn like a turtle's (Oudenodon), and some possess, in addition, two long canine teeth (Dicynodon). It is possible that the former (Oudenodon) is the female of the latter.

FIG. 499. — Skeleton of a mammal-like (theromorph) reptile, *Endothiodon*. (Courtesy, American Museum of Natural History, City of New York.)

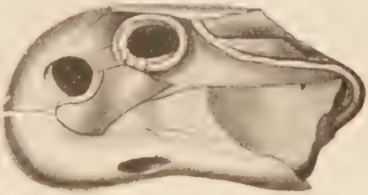


FIG. 500. — Skull of a theromorph with beak-like jaw (*Oudenodon*). The animal was herbivorous. The skull is one and a half feet long.

The theromorphs were all land animals, with limbs for the support of the body, but they varied greatly in appearance and habit.

Some (Pareiasaurus, Fig. 501 *A*, *B*) were as large as rather small cattle, about nine feet in length and standing about three and a half feet high, but with short legs and small, peg-like teeth, showing that they were herbivorous. They are believed to have been tortoise-like in habits, and probably protected themselves by digging in the ground. Associated with these in the same beds are carnivorous theromorphs (Fig. 502), some with skulls two feet in length, with long, tiger-like teeth. Attention should be called to the fact that as soon as herbivorous animals appear in any age, carnivores, often closely related to the herbivores, also occur and prey upon their less agile neighbors. So among the theromorphs we find some of massive build being destroyed and devoured by their swifter, carnivorous relatives.

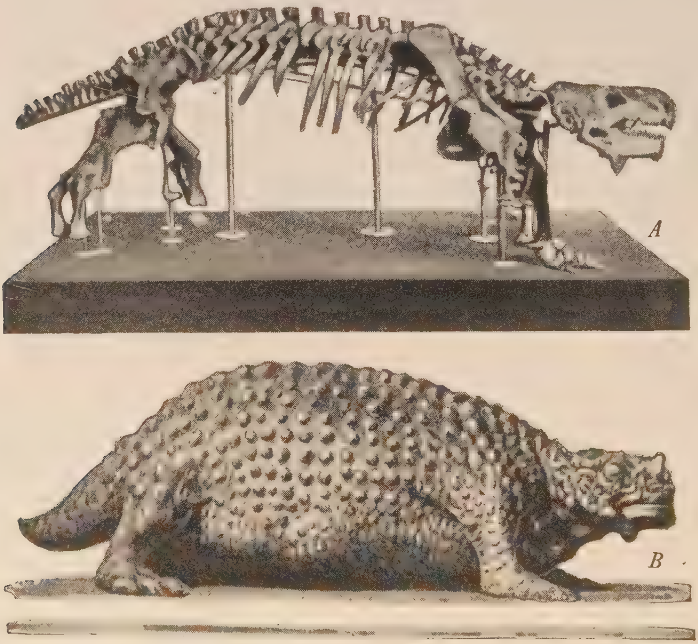


FIG. 501. — *A*, skeleton, and *B*, restoration of the herbivorous mammal-like (theromorph) *Pareiasaurus*. The length is about eight feet. The surface ornamentation of the restoration is entirely fanciful. (After Amalitzky.)

The theromorphs diverged with such rapidity in the Permian that, by its close, various groups appeared, differing slightly from one another, as has been seen. They survived the severe changes

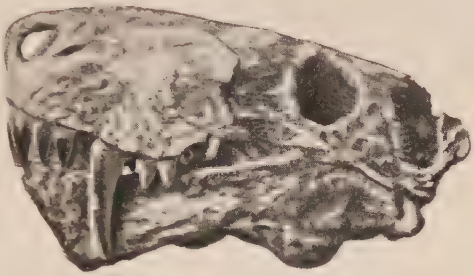


FIG. 502. — Skull of a large, carnivorous, mammal-like reptile (theromorph), *Inostranservia.* The skull is nearly two feet long.

which brought the Paleozoic to a close and spread over three continents, but became extinct before the beginning of the Jurassic. It has been suggested that their rapid development and great variation may have been due to a more oxygenated atmosphere resulting from the withdrawal of the carbon dioxide which was abstracted from the atmosphere to form coal in the Carboniferous. It is possible that their extinction was due to competition with the better organized reptiles of the Triassic.

REFERENCES FOR REPTILES WITH MAMMALIAN CHARACTERS

BROOM, R., — *South African Fossil Reptiles:* Am. Museum. Jour., Vol. 13, 1913, pp. 335-346, and Vol. 14, 1914, pp. 139-143.
HUTCHINSON, H. N., — *Extinct Monsters and Creatures of Other Days*, pp. 105-117.
LANKESTER, E. R., — *Extinct Animals*, pp. 209-222.

DINOSAURS

The preëminent land animals of the Mesozoic were the dinosaurs (Greek, *deinos*, terrible, and *saurus*, reptile), which occupied the place in nature now held by the land mammals. Some were larger than the largest animals of the present day, with the exception of a few of the whales, while others were as small as a common fowl; some walked in a more or less erect position, while others moved about on all fours; some had limbs as light as birds, while the limb bones of others were the largest and heaviest known; some were covered with a bony armor, and others were without such protection; some were very agile, others were slow-moving; some were carnivorous, others herbivorous; all were alike in having very small brains. All the continents of the world, including Australia, were occupied by them.

The dinosaurs may be separated into four groups: (1) carnivores (Theropoda), (2) unarmored quadrupeds (Sauropoda), (3) unarmored bipeds (unarmored Predentata), and (4) armored dinosaurs (armored Predentata). Of these, the first only was carnivorous, the others being herbivorous.

Carnivorous Dinosaurs. — The most striking features of the carnivorous dinosaurs were the bipedal habit and the disparity in size between the fore and hind limbs, a character which increased as the race became older, until in later forms (Tyrannosaurus, Fig. 503) the arms are so absurdly small that it is difficult to conjecture their use. As the fore limbs decreased in size and gradually relinquished their function, although never entirely abandoning it, the hind legs, in addition to their duty of supporting the weight of the body, had to assume a grasping function as well, and the claws became, in consequence, great talons, differing thus markedly from those of an earlier type (Anchisaurus). This grasping function, however, was perhaps transferred to the teeth quite as much as to the hind limbs. The earlier forms probably walked on all fours, but as the fore limbs became smaller, they stalked about on their hind legs, or possibly leaped about in kangaroo fashion with the forward part of the body lifted from the ground and balanced by the powerfully developed tail. A second group (Compsognathus, Fig. 504) differed from the above in being lighter in build, with the fore limb developed for grasping its prey.

FIG. 503. — Skull of *Tyrannosaurus*, a gigantic carnivorous dinosaur. The skull is four and a half feet long and the animal was sixteen feet high when standing. (After Prof. H. F. Osborn.)

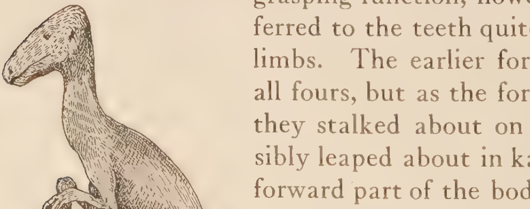


FIG. 504. — A bird-like carnivorous dinosaur, *Compsognathus*, about two feet long. (After Abel.)

The skull is very light and bird-like in some genera (Anchisaurus); and, although quite large in others (Tyrannosaurus), it is always relatively delicate. The skeleton is very light, as would be expected of animals of their habits, and the limb bones are hollow. An improvement in the teeth is noticeable from period to period; those of the earliest (Anchisaurus), although plainly for eating flesh, are not the perfect instruments possessed by those of later date (Allosaurus, Fig. 505), which are long and somewhat flattened, with serrated edges. It is not known that the carnivorous dinosaurs were especially ornamented; one genus (Ceratosaurus), however, possessed a horn on the nose, and a row of small bones embedded in the skin down the middle of the back, but aside from this, ornamentation was rare. They varied greatly in size, from animals as small as a cat to the largest carnivorous land animals that ever lived. Tyrannosaurus was 40 feet long, with teeth projecting from two to six inches from the jaw. It is possible that this last was developed to prey upon the great armored dinosaurs (p. 545) which attained their greatest size and most perfect protection in the Upper Cretaceous, shortly before the extinction of the race.

Fig. 505. — Restoration of *Allosaurus*, a carnivorous dinosaur. The small size of the fore limbs as compared with the hind is striking. (Restoration by C. R. Knight, under the direction of Professor Osborn. Copyright, American Museum of Natural History.)

The carnivorous dinosaurs are the earliest known, beginning in the Triassic and living throughout the whole of the Mesozoic.

Unarmored Quadrupedal Dinosaurs (Sauropoda). — These were the largest animals of the time. A study of the skeleton and restoration of Brontosaurus (Fig. 506) or an allied form gives a truer conception of the animal than any written description. The long neck with its absurdly small head, the large body, stout limbs, and long tail make an animal differing from any now living. Certain characters of the skeleton are unusual. The leg bones, ribs, and tail bones are solid and heavy; the head and the vertebræ of the neck and back, on the contrary, being constructed so as to combine minimum weight with the large surface necessary for the attachment of the huge muscles. The significance of the remarkably heavy bones of the lower portion of the skeleton, combined with the unusual lightness in the upper portion, is that the animals lived in the water a large part of the time. Under such conditions, the greater the weight of the bones, the greater would be the ease of walking with the body partly submerged in water. The lightness of the head and the vertebræ of the neck would be of advantage in making rapid movement of these members possible.

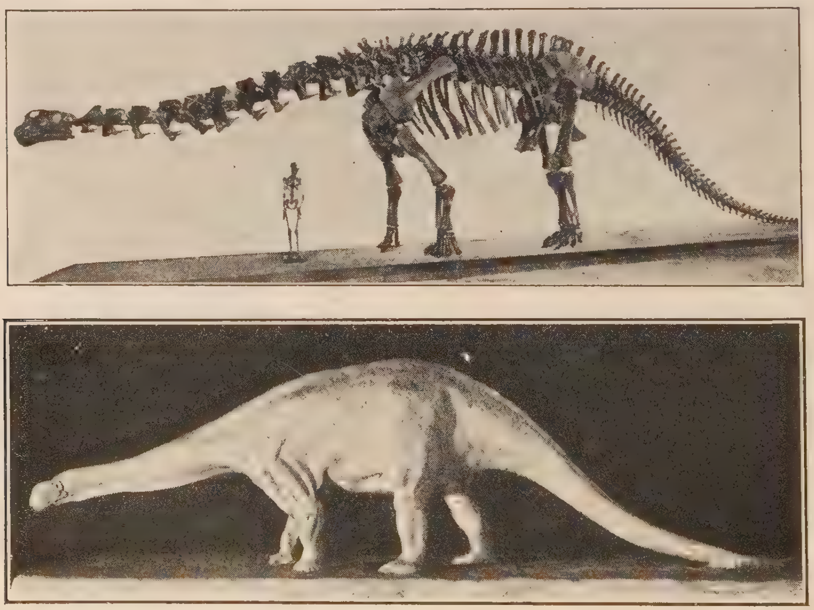


FIG. 506. — Skeleton and restoration of *Brontosaurus*. These herbivorous dinosaurs grew to be sixty feet long. (Model by C. R. Knight under the direction of Professor Osborn. Copyright, American Museum of Natural History.)

The teeth are long and either cylindrical or somewhat spoon-shaped and are set rather far apart, a shape and arrangement fitting them for biting, but not for mastication. The brain is smaller than the spinal cord.

The reptiles of this family grew to be as much as 80 feet long and stood 16 or more feet high, and some are believed to have weighed 35 to 40 tons. They lived on flat plains, such as those at the mouth of the Amazon to-day, occupied by interlacing streams and small lakes in abandoned river channels; in a warm climate with luxuriant vegetation. That the water was fresh is shown by the fossil remains with which they are associated, such as fresh-water plants, and shells, fish, crocodiles, turtles, and other dinosaurs. They went on land occasionally but not habitually, since the great weight of the solid bones would impede their movements, thus rendering them less able to escape their enemies. In the water they could swim with ease, propelled by their long tails. Their food was either floating plants, or such as were loosely attached to the bottom or banks; but they probably sometimes cropped foliage growing 20 feet above the water, which their long necks enabled them to reach. The character of the teeth precludes the possibility of hard, tough vegetation, since these are weak and not adapted to grinding. The lack of grinding teeth made it necessary for them to bolt their food, and it is interesting to note the occurrence of polished flint pebbles associated with the remains, which may have been "stomach stones" or "gastroliths," used in grinding the food after it had been swallowed.

These huge, four-footed creatures were probably descended from the carnivorous dinosaurs, either before or after the latter acquired the bipedal habit. When the carnivorous race became widespread and competition more severe, certain of them probably had a mixed diet at first, which in time became entirely herbivorous. After this change was established, the increase in size was largely a matter of abundance of food and lack of enemies. Although the body increased in bulk and changed in structure, the teeth failed to be modified to a great degree, but retained many of their ancestral characters to the end of the race. The unarmored quadrupeds first appeared either at the close of the Triassic or at the beginning of the Jurassic, and survived into the Lower Cretaceous. Their extinction may have been caused by a change in climate; by starvation as the result of the disappearance of the water plants upon which they fed; by the arrival or development of powerful enemies; or in other ways.

Unarmored Bipedal Herbivorous Dinosaurs (Unarmored Predentata). — The dinosaurs of this group were similar in general appearance to the carnivores, but differed in their less graceful build. Some of them attained a large size, being as much as 30 feet in length and standing 15 feet high (Iguanodon and Trachodon). The hind legs of some were twice as long as the fore. The heads varied considerably in different genera, being long and rather slender in most, but flat and ducklike in one specialized form, the duck-billed dinosaur (Trachodon, Figs. 507, 508). They were all alike in having the front of the jaw toothless and covered with horn. The rear portion of the jaws, however, was in one genus (Trachodon) provided with a battery of chopping and shearing teeth, composed of 45 to 60 vertical and 10 to 14 horizontal rows (Fig. 509), though the rows were not all in use at the same time, the total number of teeth in some individuals being more than 2000. Others (Iguanodon and Camptosaurus) had only one row of shearing teeth in use at one time. The teeth were replaced as rapidly as they were worn out. Teeth of this sort indicate that their possessors chopped or sheared their food and were able to live on tough, hard vegetation, such as the cycads and, perhaps, even the siliceous horsetails of the period.

FIG. 507. — Skeleton of the herbivorous, duck-billed dinosaur, *Trachodon*. (After American Museum of Natural History.)

They had three toes on the hind feet, terminating in hoofs (Trachodon), or claws (Camptosaurus). The fore limbs had three well-developed fingers, with one, or sometimes two other rudimentary ones. In a mummified specimen (Trachodon) found in Wyoming, the epidermis, which is covered with flat, bony scales, is seen to be extremely thin and the markings exceedingly fine and delicate for an animal of such dimensions (Fig. 510). The same specimen shows that the fore feet were webbed, the skin reaching beyond the fingers and forming a sort of paddle. Since these animals had strong, powerful hind legs and were without armor, it is evident that their existence depended upon their ability to escape their carnivorous enemies by speed. Some (Camptosaurus and Iguanodon) apparently lived on the dry land, while others (Trachodon) were amphibious. The latter were able, when on land, to run rapidly, and when in the water to swim, perhaps, with the speed of the crocodile, as is indicated by the great, flattened, crocodile-like tail.

Fig. 508. — Restoration of the herbivorous, duck-billed dinosaur, *Trachodon*. (Restoration under the direction of Professor Osborn. Copyright, American Museum of Natural History.)

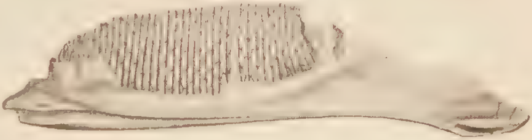


Fig. 509. — Portion of the lower jaw of *Trachodon*. The numerous teeth form a kind of pavement. (After Gilmore.)

Armored Dinosaurs (**Armored Predentata**). — The reptiles of this group were of two very different types. A representative of one family is Stegosaurus (Greek, *stegos*, roofed, and *saurus*, reptile), an animal of greater bulk than an elephant. The restoration (Figs. 511, 512) shows two rows of broad plates on either side of the backbone, varying from a few inches to two feet in height and less than an inch in thickness, except where they were embedded in the skin, and with spines near the end of the tail six inches to over three feet in length. The stout fore limbs are much smaller than the hind, but a study of the joints shows that the creatures were quadrupeds. The front of the jaw was toothless and covered with horn as in the preceding group. The teeth in the back of the mouth were weak shearing teeth, not strong enough to masticate the coarser vegetation of the time; and they must, therefore, have fed, for the most part, on succulent plants. It is possible that they lived on the land bordering marshes. One of the most remarkable features of this unique reptile is to be seen in its nervous system. The brain is estimated to have weighed only about two and a half ounces (about one-fiftieth that of an elephant of smaller size), while the enlargement of the spinal cord above the hips is twenty times larger than the brain. This "hind brain" was probably the nervous center for the great muscles of the tail. It is likely that Stegosaurus did not face its enemy, but protected itself by swinging its long, powerful tail, which, however, was not very flexible. The long hind limbs suggest the possibility of considerable speed, and the fore limbs are so constructed as to make it possible for the animal to pivot the body rapidly so as to keep the tail to the enemy. These reptiles were descended from unarmored, herbivorous dinosaurs with a bipedal habit.

FIG. 510. — The skin of *Trachodon*. The illustration is from a photograph of the impression made by the skin on the sediments in which it was buried. (After Professor Osborn.)

Two causes of the extinction of this family are suggested: the change in the vegetation to modern plants (p. 568), and the senility of the race, indicated by the spinose character. It is certainly true that an animal of such bulk, so ornamented, would not be likely to vary to such an extent as to meet radically new conditions. Stegosaurus and its armored ancestors have been found only in the Jurassic.

Another family of armored dinosaurs, differing widely from Stegosaurus, is represented by Triceratops (Greek, *tri-*, three, and *ceras*, horn) (Fig. 513), one of the largest dinosaurs of the time (Cretaceous), with a length of about 20 feet. The noticeable feature of Triceratops is the skull with its two enormous horns, three feet long and six inches in diameter at the base, one above each eye, and a shorter one on the nose. (In a closely related genus the horn on the nose was long while those above the eyes were short.) The skull projected over the neck like a great bony frill and was fringed with short, bony points. The

FIG. 511. — Skeleton of *Stegosaurus*, an armored herbivorous dinosaur. (After R. S. Lull.)

FIG. 512. — Restoration of *Stegosaurus*. (After F. A. Lucas.)

front of the jaw was sharp and parrot-like, and covered with horn, while the rear of the jaw was provided with shearing teeth. One genus of horned dinosaur (Torosaurus) had the largest head of any land animal, the skull being nearly nine feet long. The body, as well as the head, was protected, as is indicated by various spines and plates found associated with the skeleton, which were evidently embedded in the skin during life, doubtless for pro-

FIG. 513. — *Triceratops*, an armored dinosaur. It was about twenty feet long. (Restoration by C. R. Knight under the direction of Professor Osborn. Copyright, American Museum of Natural History.)

tection. The toes, five in front and three behind, were provided with hoofs.

Triceratops, unlike Stegosaurus, faced its enemies, as do cattle to-day. Punctures of the skull and frill over the neck, and broken horn cores are frequently found, showing that Triceratops often had combats with other animals. These creatures had the largest heads and smallest brains for their bulk of any of the reptiles, and were unquestionably extremely stupid, depending upon their size and armor for protection. During the life of the race, the animals increased in size and developed longer horns and a more complete frill over the neck. Triceratops had a relatively brief career, beginning in the Cretaceous and disappearing with its close.

Summary of Dinosaurs. — Dinosaurs are first known from the Triassic, at which time they were numerous and diversified, as is shown by the great number and variety of footprints in the Triassic sandstone, although few skeletons have been found. This class became more abundant, larger, and more varied in the Jurassic, culminating either in that period or in the Cretaceous. During the Mesozoic, they became more and more specialized, the specialization culminating in Stegosaurus and Triceratops among the herbivores and in Tyrannosaurus among the carnivores. After becoming adapted to widely different conditions of life, assuming many strange forms and spreading over all the continents of the world, they disappeared with the Mesozoic and left no descendants.

Migration and Extinction of Dinosaurs. — Our knowledge of the reptilian life of the Mesozoic lands is almost entirely confined to that which lived in the delta and coastal swamps of the era: the brontosaurs, the trachodons, the tyrannosaurs are all dinosaurs that lived either in swamps or on their margins. Of the upland reptiles little is known. At the close of the Jurassic the gigantic dinosaurs were almost completely wiped out, doubtless because of the draining of the swamps in which they lived and their inability to adapt themselves to other conditions. Early in the Cretaceous, however, the swamps were again populated by other huge dinosaurs as well as many of smaller size. This fauna was a new one and was not descended from that of the previous period. Either it (1) migrated from some region as yet unknown or, more probably, (2) was developed from surviving small, active denizens of the uplands which are as yet practically unknown. Towards the close of the Mesozoic (in the late Cretaceous) the modern type of vegetation was probably associated with the dominance of mammals on the uplands and, although the dinosaurs held on in the swamp regions and had adapted themselves more or less to the new vegetation, they had probably become extinct in the uplands long before the close of the period. When the elevation that divides the Mesozoic from the Tertiary occurred, it caused the disappearance of this swamp fauna, but in the following period (Tertiary) we find a swamp fauna being developed again, not from upland dinosaurs but from the mammals which had taken their place (p. 590).

Size as a Factor in Extinction. — "It is a well-known mechanical principle that the strength of a beam varies in proportion to its cross section; its weight in proportion to its mass. Hence, a beam twice as large lineally as another of the same shape will be four times as strong and eight times as heavy. Its strength, in proportion to its weight, varies inversely as its lineal dimensions. Or, to have a beam support a load proportioned to its length, its diameter must be increased by $\sqrt{2}$ for every doubling of lineal dimensions.

"Apply this principle to the skeletons and muscles of animals, and it will appear that the bones must become more massive and the muscles (whose strength of pull varies with their cross section) heavier with increase of size in the above proportion. But the proportionately heavier muscles must mean a proportionately greater amount of food required to supply power. If one animal is twice as large lineally as another, the length of its limbs will be twice as great, but its weight will be eight times as great. In order to support that weight, the bones and muscles must be eight times as strong. Since their strength depends upon their cross section, their diameter must be $\sqrt{8}$ times as large. To move the greater bulk of the larger animal will require, on account of its more massive build, somewhat more than eight times as much expenditure of energy. This energy is supplied from the food which it finds in its path. Now the larger animal, supposing its movements to be in proportion to its size, will traverse a path which will be twice as long and its reach will be twice as wide. In other words, the larger animal, with the expenditure of eight times as much energy, will cover a food area four times as large as that covered by the smaller one. If conditions be equal, it will find and secure four times as much food in the same length of time, but as we have seen, it will consume more than eight times as much energy in doing so. From this it will follow that the larger animal must use more than twice as much time in securing the necessary food to maintain its activities as the animal half as large in lineal dimensions.

"Quite obviously, this will fix a definite limit of size which will be reached when the animal expends practically all of its time in securing and eating food. After that point is reached, further increase in size can be obtained only when: (1) food becomes more abundant; (2) the race becomes adapted to a more abundant but hitherto unsuitable kind of food; (3) new adaptations are evolved for more rapid securing and digesting of food; (4) the animal is relieved of the support of part, or of most of its weight, by adopting an aquatic life. It is then subject to a new series of conditions involving a limit of size, indeed, but a much higher one than for terrestrial animals. It is a matter of common observation that while very large animals spend nearly all their time in eating, small animals spend a small proportion of theirs, and most of it in other activities.

"Now, as long as food is abundant, the larger individuals of a race have the better chances, both to repulse or escape enemies, and to drive off rivals of their own kind. Therefore, the tendency is for a race to increase steadily in size so long as food is abundant, up to a maximum above indicated. But if a scarcity of food ensues, the larger animals may all be suddenly swept out of existence, and if the smaller ones have been eliminated through the gradual evolution of the race during the period of plenty, the whole race may become extinct, or be driven to other regions, where if it is unable to adapt itself successfully to its new environment, it will finally disappear.

"For these reasons, it seems probable that we should regard all large animals as, so to speak, on the verge of extinction. They may not cross the verge for a long time, but they are always easily pushed across by some unfavorable climatic or environmental changes." (Manuscript of W. D. Matthew.)

REFERENCES FOR DINOSAURS

General

Depéret, Chas., — *Transformations of the Animal World.*
Hutchinson, H. N., — *Extinct Monsters and Creatures of Other Days*, pp. 124–186.
Jaekel, O., — *Die Wirbeltiere.*
Lankester, E. R., — *Extinct Animals*, pp. 199–202.
Lucas, F. A., — *Animals of the Past*, pp. 90–110.
Lucas, F. A., — *Animals before Man in North America*, pp. 143–172.
Lull, R. S., — *Organic Evolution*
Lull, R. S., — *Nature's Hieroglyphics:* Pop. Sci. Monthly, Vol. 66, 1904, pp. 139–149.
Marsh, O. C., — *Dinosaurs of North America:* Sixteenth Ann. Rept., U. S. Geol. Surv., 1896, pp. 143–244.
Osborn, H. F., — *The Origin and Evolution of Life.*
Von Reichenbach, E. F. S., — *Lehrbuch der Paläozoologie*, Vol. 2.
Zittel-Eastman, — *Textbook of Paleontology.*

Carnivorous Dinosaurs (Theropoda)

Matthew, W. D., — *Allosaurus, a Carnivorous Dinosaur, and its Prey:* Am. Museum Jour., Vol. 8, 1908, pp. 3–5.
The Tyrannosaurus: Am. Museum Jour., Vol. 10, 1910, pp. 1–8.

Unarmored Quadruped Dinosaurs (Sauropoda)

African Dinosaurs, a Review: Geog. Jour., Vol. 42, 1913, p. 389.
Matthew, W. D., — *The Mounted Skeleton of Brontosaurus:* Am. Museum Jour., Vol. 5, 1905, pp. 63–70.
Wieland, G. R., — *Dinosaurian Gastroliths:* Science, Vol. 23, 1906, pp. 819–821.

Bipedal Herbivorous Dinosaurs (Unarmored Predentata)

Brown, B., — *The Trachodon Group:* Am. Museum Jour., Vol. 8, 1908, pp. 51–56.
Hutchinson, H. N., — *Extinct Monsters and Creatures of Other Days*, pp. 158–171.
Osborn, H. F., — *A Dinosaur Mummy:* Am. Museum Jour., Vol. 11, 1911, pp. 7–11.

ARMORED DINOSAURS (ARMORED PREDENTATA)

HATCHER, MARSH, LULL, — *The Ceratopsia:* Mon. U. S. Geol. Surv., Vol. 49, 1907.
LULL, R. S., — *The Evolution of Ceratopsia:* Seventh Intern. Zoöl. Congr. Proc., 1910.
LULL, R. S., — *The Armor of Stegosaurus:* Am. Jour. Sci., Vol. 29, 1910, pp. 201–210.

Crocodiles. — The Triassic ancestral crocodiles have so many characters in common with the primitive reptiles (of the Pelycosaur type, p. 490) and dinosaurs that the order to which they belong is determined with difficulty. Among the changes that the crocodiles underwent during the Mesozoic, the following may be mentioned. (1) The vertebræ were biconcave (amphicœlous) in the Triassic, Jurassic, and most of the Cretaceous, as in fish, and not concave in front and convex behind (procœlous) as in modern genera. (2) The older crocodiles had the opening of the nasal passages into the mouth placed far forward, whereas living crocodiles have them placed in the extreme back of the mouth. This change in position is of advantage in that it makes it possible for the animal to breathe while it is drowning its prey. The early Mesozoic crocodiles were probably obliged to go to the land to devour their food. The marine crocodiles were doubtless descended from a group that lived in rivers, and these, in turn, from terrestrial or amphibious ancestors, although the earliest known crocodiles are marine.

Shortly before the close of the Jurassic, a side branch (Thalattosuchia) appeared, which were thoroughly adapted to a marine existence. They were covered with a bare skin, without scales, and the tail ended in a long fin. The fore limbs were paddle-like, while the hind limbs were less modified, probably because of the necessity of visiting the shore for egg-laying. After a brief existence, this family disappeared.

The crocodiles underwent a marked change early in the Cretaceous, at which time the more modern crocodiles and gavials were developed.

Marine Reptiles. — One of the most significant features of reptilian evolution is the way in which the reptiles, after they had become adapted to land life, were enabled by their superior organization and greater activity as *air*-breathing animals, to re-invade the sea repeatedly and successfully. Hardly had the reptiles become well-established upon the land, before some took to the water and became perfectly adapted to a marine existence. Members not only of one but of several classes of reptiles were so modified. It is not remarkable that some of the land reptiles should have changed their habits, when it is remembered that in the shallow waters bordering the land there was an abundant supply of fish for food, and also that there was probably some overcrowding on the land which would force the weaker species to take the food that was not to the liking of their stronger neighbors.

Ichthyosaurus (Greek, *ichthus*, fish, and *saurus*, reptile). — The most conspicuous features of reptiles of this order (Fig. 514) are the heavy body, with its pointed head and numerous teeth, and the powerful tail, with its vertical fin, adapted for rapid propulsion. Some individuals grew to be 40 feet long, although the usual size was very much less. The jaws of some individuals were five feet long and were furnished with 200 conical teeth. The eyes were large, not only in proportion to the size of the skull, but in the largest species actually attained in some perhaps the size of the human skull, and were provided with a ring of radiating, bony plates (sclerotic plates), like those of the early amphibians, which were apparently for the purpose of focusing the eye, as well as for protection.

Fig. 514. — *Ichthyosaurus*, showing both the skeleton and the "shadow" made by the carbon of the fleshy parts of the body. (Courtesy, American Museum of Natural History.)

The limbs consisted of paddles, made up of three or more rows of polygonal bones, the whole being covered with a leathery membrane. The skin was smooth and without scales. The vertebræ were biconcave, as in fishes. That Ichthyosaurus was carnivorous is shown by the contents of the abdomen, which often contains fish scales and the remains of shelled cephalopods (belemnites, p. 531).

They were remarkably well adapted to aquatic life, as is shown by the paddle-like limbs; by the outline of the body, which was so modified as to permit movement through the water with as little resistance as possible; by the sharp teeth for the catching and retention of slippery prey. The occurrence of undigested, immature young within the ribs of a number of specimens indicates that their offspring were produced alive.

Although only the later stages of the evolution of the ichthyosaurs are known, yet it is evident that they were descended from land reptiles. This is shown by the structure of the limbs of the earlier forms, which were more like the legs of land animals than were those of the later species.

The following progressive changes, fitting the animal for marine existence, have been traced: (1) The limb became more paddle-like and less leg-like, both in the structure of the skeleton and in the external shape. (2) The head became longer and better adapted for catching fish and other slippery animals. (3) The eyes became larger and more efficient for seeing in the water. (4) The neck became shorter. (5) The body gradually became more fishlike in shape and could move through the water more rapidly and with less resistance.

Ichthyosaurs began in the Triassic, culminated in the Jurassic, and lived, for a short time, in the Upper Cretaceous. During the Jurassic they appear to have been very abundant and to have occupied every sea.

Plesiosaurus (Greek, *plesios*, near, and *saurus*, reptile). — These marine reptiles are characterized (Fig. 515) by a short, stout body, a short tail, and usually by a long neck and small head. The tail was probably of greater use in steering than as an organ of propulsion, the powerful, paddle-like limbs being for that purpose. These paddles had five digits, but each digit was made up of a large number of small bones, in some cases as many as 20. Plesiosaurs varied greatly in size, some being 30 to 40 feet long, but they usually did not attain a greater length than 6 to 15 feet. One American species (Elasmosaurus), for example, was 40 feet long, with a small head and a neck 22 feet in length. "The other extreme was Pliosaurus, equally huge in bulk, but with a skull nearly 5 feet long and a neck of only a foot and a half." Most of the smaller Plesiosaurs had small heads.

The skin was smooth, without scales. The sharp, flaring teeth show that the creatures lived on animal food, possibly on small fish or some of the cephalopods which were so numerous in the seas of the time. Judging from the shape of the body, they probably swam slowly, depending upon stealth rather than speed in capturing their prey.

Fig. 515. — Restoration of *Plesiosaurus*. (Courtesy, American Museum of Natural History.)

It has been shown by a study of the neck vertebræ that the neck was too stiff for very quick movements, but would, nevertheless, be of great assistance both in capturing prey and in enabling an animal quickly to reach the surface for air. Within the body cavity of some skeletons, a large number of polished pebbles have been found — in one case a peck of them — from the size of a hen's egg to that of a baseball. These "gizzard stones" were doubtless of use in grinding the food, which was swallowed whole. If the plesiosaurs fed, to any extent, on the shelled cephalopods, some such apparatus must have been extremely useful. Plesiosaurs ranged from the Triassic to the end of the Mesozoic and reached their greatest size in the Cretaceous, and, perhaps, their greatest abundance in the Jurassic. They were not closely related to the ichthyosaurs and were probably descended from a different race of land reptiles.

Mosasaurus (Sea Lizards). — As the ichthyosaurs disappeared in the Upper Cretaceous, their place was taken by the mosasaurs (Figs. 516, 517), long, slender reptiles, with a scaly skin like that of modern snakes, which attained a length of 35 feet or more, although usually smaller. The heads were pointed and provided with sharp, stout, pointed teeth. The jaws were so constructed as to make it possible for the animal to swallow an object of almost the diameter of itself.

This was accomplished by a hinge in each half of the lower jaw (Fig. 516) which permitted it to bow outward when open. The articulation of the jaw with the skull also assisted in this process. The limbs were not as greatly modified as in the ichthyosaurs, but were completely paddle-like and resembled those of the whale. The great speed with which it could be propelled by its tail made the catching of its fish food an easy matter. Mosasaurs were descended from land animals and may have sprung from the same stock as modern reptiles. They were not well established until the Upper Cretaceous, in which period they rapidly diverged and swarmed the Atlantic and Gulf coasts and the interior seas. They had a wide distribution, being found in North and South America, Europe, and as far south as New Zealand. They disappeared with the Mesozoic, after having had a comparatively short life.

FIG. 516. — Skeleton of a Cretaceous *mosasaur* about sixteen feet long. (After Williston.)

FIG. 517. — Restoration of a Cretaceous *mosasaur*. (Painted by C. R. Knight under the direction of Prof. H. F. Osborn. (Copyright, American Museum of Natural History.)

REFERENCES FOR MARINE REPTILES

ICHTHYOSAURS

HUTCHINSON, H. N., — *Extinct Monsters and Creatures of Other Days*, pp. 59–75.
LANKESTER, E. R., — *Extinct Animals*, pp. 225–229.
OSBORN, H. F., — *Ichthyosaurs:* Century Mag., Vol. 69, 1905, pp. 414–422.
WILLISTON, S. W., — *Water Reptiles of the Past and Present*, pp. 107–125.

PLESIOSAURS

LULL, R. S., — *Organic Evolution.*
MATTHEW, W. D., — *The New Plesiosaur:* Am. Museum Jour., Vol. 10, 1910, pp. 246–250.
WILLISTON, S. W., — *Water Reptiles of the Past and Present*, pp. 73–101.

MOSASAURS

HUTCHINSON, H. N., — *Extinct Monsters and Creatures of Other Days*, pp. 187–198.
LUCAS, F. A., — *Animals of the Past*, pp. 48–56.
OSBORN, H. F., — *A Complete Mosasaur Skeleton:* Am. Mus. Nat. Hist. Mem., Vol. 1, 1899, pp. 167–188.
WILLISTON, S. W., — *Water Reptiles of the Past and Present*, pp. 148–167.

GENERAL

LULL, R. S., — *Organic Evolution.*
WILLISTON, S. W., — *Water Reptiles of the Past and Present*, pp. 59–72.
WOODWARD, A. S., — *Vertebrate Paleontology.*
ZITTEL-EASTMAN, — *Textbook of Paleontology.*

Turtles. — It is an interesting fact that, although turtles are so widely different from other forms at the present, yet, even when first known, — in the Upper Triassic, — they are as typically turtle-like as now. Jurassic turtles were abundant, had a world-wide distribution, and were closely related to existing genera. The first strictly marine turtles (in which the feet are modified to form "flippers") have been found in the Cretaceous, one of which, Archelon, was of great size, the head measuring three feet in length, the total length of the animal being 12 to 14 feet. In this case, the shell proper had disappeared, and the broadened ribs were possibly covered with a soft skin, as in some living marine turtles (Dermochelys). Land turtles did not appear until the Tertiary.

A number of suggestions as to the origin of turtles have been offered, but since the earliest known species are far from being generalized, the whole matter is, as yet, in doubt.

REFERENCES FOR TURTLES

Hay, O. P., — *The Fossil Turtles of North America:* Carnegie Institution of Washington, Pub. No. 75, 1908.

Wieland, G. R., — *Archelon, etc.:* Am. Jour. Sci., Vol. 2, 1896, pp. 401–412.

Williston, S. W., — *Water Reptiles of the Past and Present*, pp. 216–241.

Flying Reptiles (Pterosaurs). — Either because of the overcrowding of the land, or for some other reason, a race of flying reptiles was developed during the Jurassic and Lower Cretaceous, and occupied the realm of the air, in which there was no competition.

Fig. 518. — A Jurassic *pterosaur* (*Rhamphorynchus*). (After Von Reichenbach.) Length about twenty inches.

The pterosaurs (Figs. 518, 519, 520) are as extraordinary, in many ways, as any animal that ever lived. They had a short body, hollow bones, a rather large but light head, and jaws which at the beginning of the race were provided with slender teeth, but which in some highly specialized later genera were toothless and sheathed with horn, as in modern birds. The most remarkable and characteristic features, however, were the large, membranous wings, supported by one greatly elongated finger, the fourth. The breastbone, to which the muscles of flight were attached, was large and keeled, and the shoulder girdle was strong. Some had long tails with a kind of rudder at the extremity, and others were tailless. The pterosaurs varied greatly in size; some were as small as sparrows, some were the size of partridges, while others were the largest flying creatures that ever lived, the wings measuring over 20 feet from tip to tip (Fig. 520).

One of the best known and least specialized genera of the Jurassic pterosaurs (Dimorphodon; Greek, *dimorphos*, two-formed, and *odont-*, tooth) (Fig. 519) had, as the name implies, two kinds of teeth, those in front of the jaw being sharp and strong and fitted for tearing, while those in the back of the jaw were small and sharp, with a sawlike edge. This pterosaur could probably walk on all fours or on its hind legs alone. When standing on its hind legs, it was less than two feet high, and its wings had a spread of a little more than four feet. The wings (Fig. 519) were formed by a naked membrane, without feathers or hair, stretching from the body to the greatly elongated fourth finger. Although the least specialized of the pterosaurs, they possessed few characters connecting them with other reptiles.

FIG. 519. — A Jurassic *pterosaur* (*Dimorphodon*). The extreme length from the tip of the nose to the end of the tail was a little more than three feet. (Modified after Seeley.)

FIG. 520. — Skeleton of *Pteranodon*, the most highly specialized of the pterosaurs (Cretaceous). Everything was sacrificed for flight and feeding. The wings measured almost twenty feet from tip to tip. (After Eaton.)

Perhaps the most highly specialized animal that ever existed was a pterosaur (Pteranodon; Greek, *pteron*, wing, and *a-odont-*, without a tooth) that lived in the Upper Cretaceous. In this animal (Fig. 520) it would seem that everything possible was sacrificed for flight. The upper portion of the body, the wing, shoulder, and breast were all extraordinarily strong, while the lower portion of the body and hind limbs were very weak. The head was highly developed, being long and slender, with a dagger-like beak and toothless jaws. The head was about four feet long, the body only slightly longer. It is thought that, notwithstanding its large size, it was so lightly built that in life it did not weigh more than 25 pounds. In fact, the bones of the largest specimen, even as petrified, do not weigh more than 5 or 6 pounds. When not sailing in the air, pteranodons probably spent their time suspended from cliffs or trees by their slender, clawed fingers. Pteranodons lived upon fish, as is shown by the fishbones and scales found within their skeletons. Because of the small pelvis, we must suppose that if they laid eggs, the eggs were very small.

Because of the high degree of specialization of the earliest pterosaurs, nothing definite can be said as to their ancestry, but it is possible that pterosaurs, carnivorous dinosaurs, and birds all sprang from a common ancestor (such as Euparkeia). (Broom.) Although flying animals they were not the ancestors of birds. The first evidence of their appearance has been found in the later Triassic, but they did not reach North America until after the middle of the Jurassic, at which time they swarmed over the epicontinental seas. None lived into the Upper Cretaceous.

REFERENCES FOR PTEROSAURS

Chamberlin and Salisbury, — *Geology*, Vol. 3, especially pp. 101 and 179.

Eaton, G. F., — *Pteranodon:* Am. Jour. Sci., Vol. 17, 1904, pp. 318–320.

Hutchinson, H. N., — *Extinct Monsters and Creatures of Other Days*, pp. 199–210.

Lucas, F. A., — *Animals before Man*, pp. 209–219.

Lucas, F. A., — *The Greatest Flying Creature, etc.:* Smithsonian Inst. Rept., 1901, pp. 654–659.

Lull., R. S., — *Organic Evolution.*

Seeley, H. G., — *Dragons of the Air.*

Williston, S. W., — *Winged Reptiles:* Pop. Sci. Monthly, Vol. 60, 1902, pp. 314–322.

Williston, S. W., — *The Wing Finger of Pterodactyls:* Jour. Geol., Vol. 19, 1911, pp. 696–705.

Zittel-Eastman, — *Textbook of Paleontology.*

Toothed Birds

Archæopteryx. — If the skeletons of the earliest known bird had not had feathers associated with them, it is probable that they would have been described as belonging to the Reptilia, with some birdlike characters. This oldest bird (Archæopteryx; Greek, *archaios*, old, and *pterux*, a wing) (Fig. 521) was about the size of a small crow, with a small, stout, birdlike head and a birdlike brain, but its jaws, instead of being of horn as in modern birds, were provided with sharp, conical teeth. The wing was peculiar in having three reptile-like claws, by means of which the bird could crawl about the trees, instead of flying. The hind limb was much like that of modern birds and had four digits. The vertebræ were biconcave, as in fish and some reptiles. The tail was one of the most peculiar features in that it was vertebrated, with a pair of feathers springing from each joint. In modern birds, the feathers are arranged like the sticks of a fan. Archæopteryx was not well adapted for flying, as is shown by the poorly developed breastbone. With the exception of occasional short flights, it probably soared somewhat as flying squirrels do today. Birds probably did not have dinosaurian ancestors, but were presumably derived from a group of primitive, dinosaur-like reptiles that were capable of running on their hind legs. Archæopteryx is not known to have lived in America; and only a few specimens have been found in Europe, all of which are from the Jurassic.

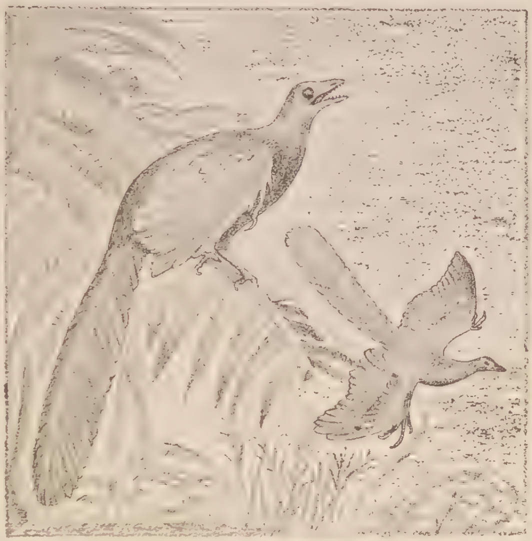


FIG. 521. Restoration of *Archæopteryx* (Jurassic). The long vertebrated tail, clawed wings, and teeth are well shown. (Modified after Hutchinson.)

Hesperornis. — This bird (Fig. 522) was adapted for life in water instead of in air. It was the largest bird of its time, attaining a length of nearly six feet. The jaws were supplied with small teeth which, instead of being set in sockets as in Ichthyornis (p. 562) were in grooves. As in snakes, the jaws were so constructed as to permit the bird to swallow large prey. The tail was vertebrated, but was intermediate between Archæopteryx and modern birds. Hesperornis was perfectly adapted for aquatic life. Wings were wanting, and only a rudimentary bone was left to show that a wing existed in its remote ancestors. The feet were modified in a manner not found in any other bird, living or fossil, being so joined to the leg as to turn edgewise as the foot was brought forward. The resistance of the water was in this way lessened. This adaptation to aquatic conditions may have been so perfect that not only flying, but walking as well, was abandoned. The bird was covered with soft feathers, as fossil impressions show. Hesperornis lived only in the Upper Cretaceous.

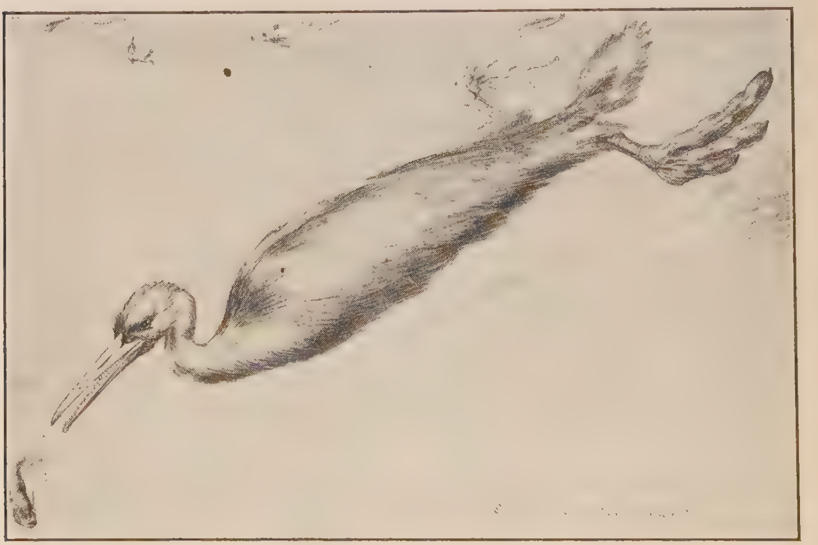


Fig. 522. — *Hesperornis*, a diving, toothed bird of the Cretaceous. (Restoration under the direction of F. A. Lucas.)

Ichthyornis (Greek, *ichthus*, fish, and *ornis*, a bird). — This bird (Fig. 523) was about as large as a pigeon and must have looked very much like a modern bird. It was, however, radically different in some particulars. Its slender jaws were toothed, the teeth being small and set in sockets, twenty on each side below and fewer above. The vertebræ were biconcave, like those of fishes and many extinct reptiles but no modern bird. The tail was about midway between the vertebrated tail of Archæopteryx and those of the birds of the Tertiary and to-day. The strongly keeled breastbone for the attachment of the muscles proves that it was a powerful flyer. Although Ichthyornis shows a distinct advance over Archæopteryx in its less vertebrated tail, its power of flight, and the loss of the claws on the fore limbs, an equal or greater change is to be seen between the Cretaceous birds and those of the Tertiary.

It is interesting to speculate upon the cause of the abandonment of teeth for a horny jaw both by birds and pterosaurs. A toothed jaw would insure the retention of every fish captured, but would prove a hindrance to its being swallowed quickly. Possibly toothed birds and pterosaurs were obliged to go to land before being able to devour their food, but those with horny beaks could bolt their food on the wing.

Fossil birds are comparatively rare, even from the rocks of periods when birds were abundant, because of the lightness of the skeletons, which caused the carcasses to float on the seas for a long time before sinking to the bottom, with the result that the skeletons were usually devoured by fish or beasts of prey before they had a chance to be buried in the sediments. Bird fossils are rare in the Mesozoic also since they are not now and were not then to any extent swamp dwellers, and what is known of Mesozoic land life is chiefly limited to the fauna of the swamps. Because of this, it is probable that only a small part of the bird life of the Cretaceous is known.

FIG. 523. — *Ichthyornis*, a small, toothed bird with strong powers of flight (Cretaceous). (After Marsh.)

REFERENCES FOR BIRDS

LUCAS, F. A., — *Animals of the Past*, pp. 70–89.

LUCAS, F. A., — *Beginnings of Flight:* American Museum Journal, Vol. XVI, pp. 5–11.

MARSH, O. C., — *Birds with Teeth:* Third Ann. Rept., U. S. Geol. Surv., 188, pp. 45–88.

NEWTON, — *A Dictionary of Birds.*

ZITTEL-EASTMAN, — *Textbook of Paleontology.*

MAMMALS

A few very small lower jaws have been discovered in Triassic deposits of America and Europe (Dromatherium, Fig. 524), which have been considered by some students as reptilian and by others as mammalian. If they are reptilian, they are theromorphs; if mammalian, either monotremes (egg layers that suckle their young, like Platypus), or marsupials (mammals that produce their young in an immature condition, like the opossum). It is suggestive, however, to note that creatures that are either reptiles with strong mammalian characters or mammals with well-marked reptilian characters existed before true mammals made their appearance. With one exception, the few mammalian remains found in the Mesozoic are of small size, indicating animals not larger than rats. Those of the Jurassic and Cretaceous appear to be insectivores and to be either monotremes (egg-laying mammals) or marsupials, but none clearly belong to the highest type of mammals (Eutheria, common mammals of to-day) nor are they closely related to other forms.

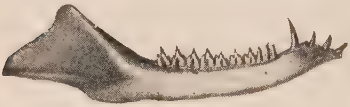


FIG. 524. — Jaw of either a primitive mammal or a theromorph reptile (Triassic), twice the natural size. (After Emmons.)

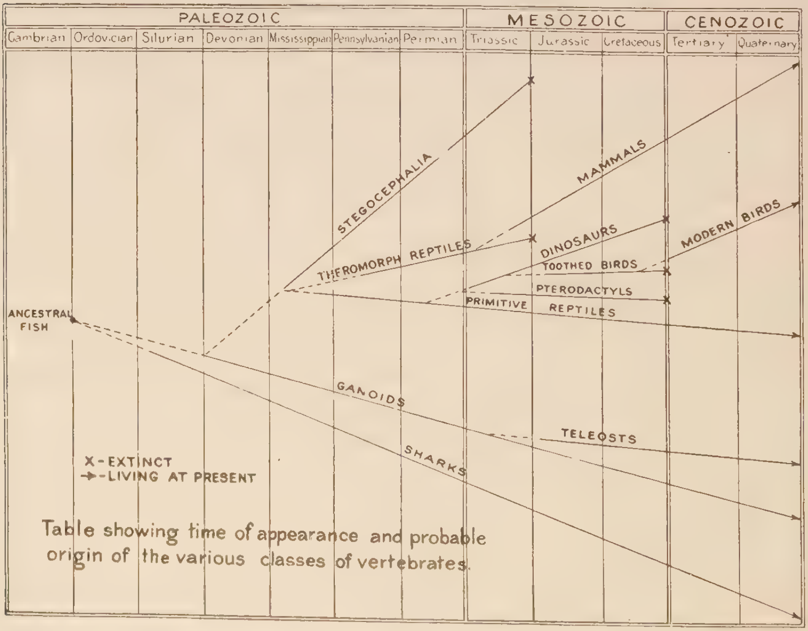


FIG. 525. — Table showing the probable relationships of vertebrates, with their geological distribution.

The probable relationships of the mammals and other vertebrates are shown in the table (Fig. 525).

REFERENCES FOR MAMMALS

SCOTT, W. B., — *A History of Land Mammals in the Western Hemisphere*, pp. 642–644.
WOODWARD, A. S., — *Vertebrate Paleontology*, pp. 246–260.

PLANTS

The vegetation of the Mesozoic is of great interest, since it was during this period of world history that the now dominant types of plants were introduced. Mesozoic plant life, as indeed does the plant life of all geological ages, affords a reliable clue to the climatic and physical conditions which prevailed during the several periods, and incidentally offers, to some degree, an explanation of the striking changes which took place in the animal life.

In discussing the vegetation of the Mesozoic, a division into Lower and Upper should perhaps be made, because of the introduction of modern plants (angiosperms) in the Lower Cretaceous and the subordination of the typical early Mesozoic plants in the Upper Cretaceous.

Owing to considerations, physical and otherwise, concerning which there is not complete agreement, the lower part of the Triassic affords but scant remains, and it is not until we come to the upper part (Rhætic) that the plant remains can be really dignified as a flora. In North America there are less than 150 species, and the entire Triassic flora of the world probably does not exceed 300 or 400 forms.

Horsetails. — The *horsetails*, which entirely replaced the calamites of the Carboniferous, do not appear to have differed markedly from those now living, except that they were often of larger size, some having been reported that are from five to eight inches in diameter. It is presumed that they formed dense growths, like canebrakes, in or along swamps, marshes, or lakes, as do certain of their living representatives to-day, the largest of which — a South American species — is an inch in diameter and 20 or 30 feet in height.

Cycads. — Among the most characteristic and abundant plants of the Triassic and Jurassic was the great group of *cycads* (using the term in the broad sense to include the Bennettitales and Cycadales). They were similar in general appearance to those of the present, but differed in some important characters. Fossil cycad trunks (Fig. 526) are generally short and stout, never apparently reaching a greater height than three or four feet, and usually much less. As in modern cycads, a crown of long, stiff leaves sprang from the top of the trunk, which was scarred throughout by the leaf-bases of previous leaves. Some fossil cycads from South Dakota are so completely preserved that such delicate structures as immature leaves, flowers, pollen, and some seeds with their contained embryos, are retained in remarkable perfection.

Fig. 526. — A group of cycad trunks (Bennettites). (After Wieland.)

Because of this perfection of preservation, almost as much is known of the structure of this extinct group as of its living relatives. The position of the seed-bearing cone and the large leaves bearing the pollen sacks of a fossil cycad is well shown in the diagram (Fig. 527). Cycads, which appear to have grown on the dryer lowlands about the swamps, had their origin in the Permian, reached their greatest abundance in the Jurassic, and are rare after the close of the Mesozoic.

Ferns were common throughout the era, wherever the conditions were favorable for their growth.

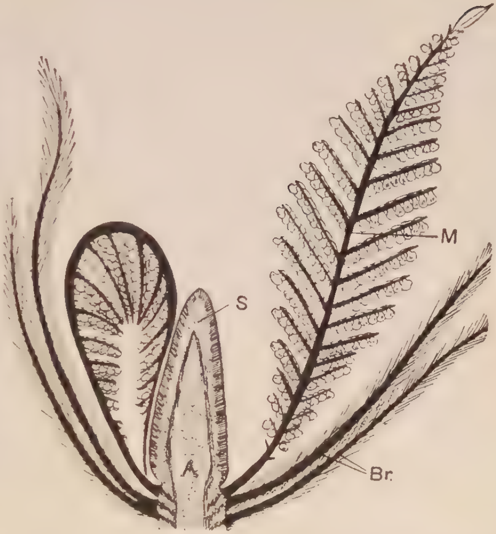


FIG. 527. — Diagram of a complete cone of Bennettites, much enlarged. (After Wieland.) The large leaves, *M*, bear pollen sacks, and the central cone *S* is seed-bearing.

Gymnosperms. — The *conifers* (evergreen trees of to-day) lived on the higher lands during the Mesozoic and were represented by pines, cypresses, yews, and araucarias (monkey-puzzle), the last being especially abundant in the Jurassic. The sequoia (redwoods and "big trees" of California) had a notable development in the Upper Cretaceous. Because of the resinous character of the wood of the coniferous trees, it was often preserved, sometimes in a remarkable degree of perfection. On the whole, the Mesozoic conifers were not very different in general appearance from those of to-day. The early Triassic forms, however, were somewhat dwarfed, while those of the later Triassic were gigantic trees, often over 100 feet in length and from four to eight feet in diameter.

The maidenhair tree, *ginkgo*, was abundant and had a world-wide distribution in the Lower Mesozoic. This once numerous family is now represented by but one species, which probably would have been long since extinct had it not been preserved by cultivation about the Buddhist temples in Japan and China. The modern ginkgo comes of a long-lived family. Evidence is at hand indicating that, if

FIG. 528. — Leaves of the modern ginkgo tree.

not the existing genus, at least a closely related one lived in the Paleozoic. The impressions of the leaf, seeds, and male cones of Jurassic trees are very similar to those of the trees now living (Fig. 528).

Angiosperms. — The *flowering plants* are, at present, the commonest of all plants, four sevenths of the existing species belonging to this class. They have, however, a much shorter known history than the conifers and various other groups, since no positive evidence is at hand of their existence prior to the Lower Cretaceous. At the beginning of this period, the horsetails, cycads, conifers, and ferns were the common and conspicuous forms; but, before its close, flowering plants of both divisions (monocotyledons, represented to-day by palms, lilies, and grasses, and dicotyledons, of which the elm, rose, and clover are examples) had become prominent. The sassafras, fig, willow, magnolia, tulip tree, laurel, and others have been recognized. In the Upper Cretaceous the flowering plants became even more conspicuous, and are represented, among many others, by palms, beeches, birches, chestnuts, and poplars.

The introduction of flowering plants was, perhaps, the most important and far-reaching event in the whole history of vegetation, not only because they almost immediately became dominant, but also because of their influence upon the animal life of the succeeding periods. Hardly had flowers appeared, before a great horde of insects which fed upon their honey or pollen seem to have sprung into existence. The nutritious grasses and the various nuts, seeds, and fruits afforded a better food for non-carnivores than ever before in the history of the world. It was to be expected, therefore, that some new type of animal life would be developed to take advantage of this superior food supply. As we shall see in the discussion of the Tertiary, the mammals, which kept a subordinate position throughout the Mesozoic, rapidly took on bulk and variety and acquired possession of the earth as soon as they became adapted to this new food, quickly supplanting the great reptiles of the Mesozoic.

The flowering plants (angiosperms) had their origin, as far as is known, on both sides of the North Atlantic during the Lower Cretaceous. Some of the earliest of these are somewhat generalized, but do not give a positive clue to the group from which they were descended. Just when and where they began we do not know, but once started they spread rapidly and widely, and before the close of the Lower Cretaceous had reached California, Alaska, Greenland, and Bohemia.

REFERENCES FOR PLANTS

Chamberlin and **Salisbury**, — *Geology*, Vol. 3.
Knowlton, F. H., — *The Relations of Paleobotany to Geology:* Am. Naturalist, Vol. 46, 1912, pp. 207–215.
Seward, A. C., — *Fossil Plants.*
Scott, D. H., — *Studies in Fossil Botany.*
Scott, D. H., — *Evolution of Plants.*
Scott, D. H., — *Paleobotany:* Encyclopedia Brittanica, 11th edition.
Scott, W. B., — *An Introduction to Geology*, pp. 668, 684, 714–715.
Stopes, M. C., — *Ancient Plants.*
Wieland, G. R., — *American Fossil Cycads.*

CLIMATE

Triassic. — The climate of the Triassic of North America, Central Europe, and North Africa seems, as a whole, to have been arid, although some areas of considerable extent had sufficient rainfall to produce a luxuriant vegetation. The proofs of aridity are to be found in the widespread occurrence of gypsum and salt, and in the prevalence of " red beds " (rock of a red color). It is well known that the deposition of salt and gypsum is the result of evaporation in excess of supply, such as can happen only in arid regions. The explanation of the red color of sedimentary rocks is not so clear. If organic matter, either animal or plant, is plentiful in sediments, the contained iron will be in the form of the gray iron carbonate instead of the red iron oxide. At the present day, for example, although the rocks of the southern Appalachians are weathered to red clay many feet deep, the sediments derived from them are gray when deposited, because of the reduction of the iron oxide by the plant débris which they inclose. A less abundant flora, due to decreased rainfall, might readily result in the deposit of red sediments without reduction. On the other hand, attention has been called to the fact that, probably in many cases, red sediments were laid down in regions where the rainfall was undoubtedly not small. (White.)

The Triassic red sandstones and shales of the Connecticut valley, with their innumerable reptilian footprints, indicate aridity in another way. It was formerly thought that these deposits were laid down in a great estuary of the sea, under conditions similar to those of the Bay of Fundy to-day, in which the difference between high and low tide was great. As a result, during several hours of the day, extensive mud flats were uncovered, upon which the saurians of that time walked or ran in search of food or water and left their tracks. It has been shown, however, that a number of hours at least must elapse under known conditions, before mud can dry sufficiently to form sun cracks and to retain the footprints of animals. If these conclusions are correct, we must believe that the deposits of the Connecticut valley and New Jersey were laid down in river valleys analogous to the Great Valley of California and other structural basins. In the shallow lakes which occurred, such for example as Tulare Lake in California, the depth of the water was greatly reduced by evaporation during longer or shorter periods, and the bottom of the shallower portions of the seas was exposed for several days or weeks at a time.

There is abundant proof, however, that in certain regions the rainfall during the Triassic was plentiful, due probably, as to-day, to the presence of mountain ranges which caused abundant precipitation on one side and deserts on the other. In Virginia, for example, beds of coal aggregating 30 to 40 feet in thickness indicate long-continued swamp conditions. Horsetails four to five inches in diameter, ferns of large size, some of them tree ferns, prove that the climate was favorable for luxuriant growth. The petrified trees of Arizona, some of which were eight feet in diameter and more than 120 feet high, do not indicate aridity, nor, for that matter, do they prove a moister climate than that of Arizona to-day, in which the great pines south of Flagstaff flourish. The complete or nearly complete absence of rings in the tree trunks indicates that there were no, or but slight, seasonal changes, due to alternations of heat and cold or wet and dry periods.

Jurassic. — The presence of luxuriant ferns, many of them tree ferns, horsetails of large size, and conifers, the descendants of which live in warm regions, all point to a moist, warm, subtropical climate during the greater part of the Jurassic; although arid regions unquestionably existed. The animals also indicate a warmer climate in the northern regions than at present. Saurians and ammonites lived within the Arctic circle, and corals 3000 miles farther north than now. The presence in the late Jurassic of rings in the tree trunks of northern species shows that slight seasonal changes occurred.

Cretaceous. — The climate of the Lower and Upper Cretaceous seems to have been milder than at present, even that of Greenland being temperate or warm temperate. The distribution of marine fossils indicates the existence of climatic zones according to latitude, but the vegetation does not show this so clearly; for example, oaks, maples, and magnolias grew in Greenland and nearly as far north as

Alaska, in the Lower Cretaceous. If a cold, but not frigid, polar sea existed from which currents extended southward, the apparent contradiction in the evidence of the plants and animals would be explained.

REFERENCES FOR CLIMATE

KNOWLTON, F. H., — *Succession and Range of Mesozoic and Tertiary Floras:* Outlines of Geologic History (Willis and Salisbury), pp. 201–207.

LULL, R. S., — *The Life of the Connecticut Trias:* Am. Jour. Science, Vol. 33, 1912, pp. 397–422.

SCHUCHERT, CHAS., — *Climates of Geologic Time:* Carnegie Institution of Washington, Pub. 192, 1914, pp. 263–298.

WHITE and KNOWLTON, — *Evidences of Paleobotany as to Geological Climate:* Science, Vol. 31, 1910, p. 760.

COAL

Triassic. — Coal beds occur in the four systems of the Mesozoic. In the United States, coal of the Triassic Age was worked as early as 1700 in the Virginia-North Carolina coal fields, but these deposits are of more interest historically than economically. Coal of this age occurs also in Germany, Sweden, South Africa, and Australia, and, as in North America, is composed of horsetails, ferns, and cycads. Coal in commercial quantities occurs in Hungary, in several of the countries of Asia, in Australia, and New Zealand, in Jurassic formations.

Cretaceous. — The Lower Cretaceous rocks bear coal locally in British Columbia and Alaska. The great coal-producing system of western North America is the Upper Cretaceous, the total quantity and extent of the coal formations being comparable to those of the Carboniferous. The quality is, however, usually inferior to that of the Carboniferous coal, being largely lignite, although some bituminous coal of excellent quality is produced, and in a few localities anthracite coal, made from bituminous and lignite coal by the intrusion of igneous rocks, is worked. It is interesting in this connection to note the presence of charred wood and charcoal in some of the Cretaceous beds, showing the existence of fire during the period. Although workable coal is found in all the stages of the Upper Cretaceous of western North America, that of the Montana and Colorado stages is most important. The so-called Laramie coal has been found to belong largely to the Montana stage of the Upper Cretaceous and to the lowest stage (Fort Union) of the Tertiary.

CHAPTER XXI

CENOZOIC ERA: AGE OF MAMMALS. TERTIARY PERIOD

Comparison of the Life at the Close of the Mesozoic and the Beginning of the Cenozoic.—The Age of Reptiles apparently came abruptly to a close, and the Age of Mammals began. In the last stage of the Upper Cretaceous (Lance) the dinosaurs were in the "climax of their specialization and grandeur." The bulky Triceratops (p. 548) with his great horned head, the amphibious duck-bill dinosaur (Trachodon, p. 544) as well as other armored dinosaurs, roamed about in the Rocky Mountain region. At the same time lived the swift and powerful Tyrannosaurus (p. 540) which doubtless preyed upon some of these herbivorous relatives. Associated with these great reptiles were small mammals (p. 564) of lowly organization and of small size. "One of the most dramatic moments in the life history of the world is the extinction of the reptilian dynasty which occurred with apparent suddenness at the close of the Cretaceous, the very last chapter in the Age of Reptiles." (Osborn.) This does not mean that the reptiles were wiped out of existence by some great cataclysm, but that, as measured by geologic time, the wane was rapid. What cause or causes produced this great result cannot be stated definitely.

(1) Change in vegetation has often been called in to account for the extinction of various groups of animals, but we find much the same vegetation after the extinction of the dinosaurs as when they were abundant and at the summit of their specialization. Such trees as the fig, banana, sequoia, ginkgo, oak, and sycamore passed from one period to the other without alteration. This being the case, a change in food, unless under exceptional conditions, could not have been a cause of dinosaurian extinction. Moreover, since the vegetation remained so nearly the same at the critical time, it is not probable that the climate had been greatly modified. (2) It has also been suggested that the cause of their extinction was their inability to compete with the more agile and intelligent mammals, and the fact that their young, not having the maternal care of these higher vertebrates, were easily

captured and destroyed by carnivorous mammals. Whatever the cause or causes, the great reptiles — marine, flying, and terrestrial — disappeared; and mammals soon occupied all the places in nature formerly held by them, the only reptiles surviving being those whose habits or inconspicuous form saved them from their competitors.

The Mesozoic types of birds with toothed jaws and vertebrated tails (p. 560) were replaced by the toothless birds with which we are familiar.

The difference between the invertebrate life at the close of the Mesozoic and at the beginning of the Tertiary is not great, although the species are different. The most noticeable feature, perhaps, is the absence of an abundant and varied cephalopod fauna which was so conspicuous in the Cretaceous seas.

Subdivisions of the Cenozoic Era. — The Cenozoic (Greek, *kainos*, recent, and *zoe*, life) is the last era in the world's history. It is also called the Age of Mammals because of their predominance and importance from the beginning of the era, to, and including the present.

Cenozoic	Quaternary	Recent
		Pleistocene (or Glacial)
	Tertiary	Pliocene (Greek, *pleion*, more, and *kainos*, recent). More than half of the mollusca are living species.
		Miocene (Greek, *meion*, less, and *kainos*, recent). Less than half of the mollusca are recent species.
		Oligocene (Greek, *oligos*, little, and *kainos*, recent). Less than one fourth of the mollusca are recent.
		Eocene (Greek, *eos*, dawn, and *kainos*, recent). With few or no modern species of mollusca.

This era is separated into two periods, Tertiary and Quaternary, the first lasting until the appearance of the great ice sheets and the second from that time to the present. They were of very unequal duration, the former being several millions of years long, the latter probably less than one million. The life of the Tertiary became more and more modern as the end was approached, and the period is subdivided into four epochs, as is shown by the above table. In determining the age of the rocks of the Tertiary, however, the percentage of modern species is not computed, but the separation is based on certain species which had a short life and are characteristic of a single epoch.

Physical Geography of the Tertiary. Eocene

The deformations that raised the Rocky Mountains and drained the western interior of North America apparently affected the continent as a whole, and for a time the Atlantic and Pacific coasts were farther out than in the period under discussion (Fig. 529); thus portions of the Cretaceous sea bottom were exposed to erosion. This is shown by the old land surfaces (unconformities) — not, however, universal — between the Eocene and the underlying formations, on both the Atlantic and Pacific borders of the continent. Since, when traced eastward, the Cretaceous peneplain disappears beneath Eocene deposits, we know that the beginning of the latter epoch was marked by submergence. An important point to be kept in mind in our discussion of the physical geography of the Tertiary is that North America has been a relatively stable continent since the close of the Cretaceous.

Atlantic and Gulf Coasts. — On the Atlantic coast, deposits occur on Marthas Vineyard island, but not on the mainland of New England or Canada (Newfoundland was probably a part of the continent at this time), and extend from New Jersey into Texas, by way of Alabama and Mississippi, then up to the mouth of the Ohio River and thence southwest. The Atlantic deposits of this period are usually loose and incoherent sands, clays, and green-sand marls, derived largely from the Cretaceous formations but also to some extent from older formations. In the Gulf regions the rocks are more consolidated, sandstones, limestones, and shales being common. Extensive lignite deposits occur in Texas and Louisiana, which may become valuable at some future day when bituminous coal is more costly than now. These lignite beds were formed from the peat bogs that existed on poorly drained portions of the low-lying coast, just as peat is being formed in similar regions to-day.

Pacific Coast. — In the western portions of the continent the rocks of the period are, for the most part, sandstones and shales, with occasional conglomerates and tuffs, which rest unconformably on the older rocks in many places, but in others are conformable, the division being determined by the change in the fauna. The diatomaceous shales which occur at the top of the series (in the vicinity of Coalinga, California) should be mentioned, since they are believed to be the source of important deposits of petroleum.

During the early part of the Eocene, marine conditions prevailed over a considerable territory, but these later gave way to brackish or fresh-water swamp conditions. The physical history during the latter part of the period is one of persistent but frequently interrupted submergence, in which the alternation of many coal beds (some workable) with deposits of fine shale and coarse sandstones indicates that, during this great subsidence, the depth of the water frequently changed. At times the sinking proceeded more rapidly, and the deepened water was then filled with sediment, " until the tide-swept flats became marshes and, for a time, vegetation flourished vigorously in the moist lowlands" (Willis), this rotation being repeated intermittently. This condition is believed to have prevailed in Alaska, western Oregon, and the Great Valley of California. Most of the coal of the west coast belongs to this epoch, making this the " Eocene Carboniferous" of the west. In the later Eocene, elevation and erosion, accompanied by volcanic outbursts and extensive lava flows, occurred in Oregon and Washington. The presence of Atlantic species in the marine deposits shows that an oceanic connection, probably in the Central American region, was in existence for a time.

Western Interior. — The Eocene deposits of the western interior (Fig. 529), with the exception of a few small areas in Colorado, are confined to the region between the Sierra Nevadas and the Rocky Mountains. It is thought that the region under discussion was not greatly elevated above sea level, although the summits of the mountains probably stood sufficiently high above the general level of the plains to permit the vigorous erosion which was in progress during the epoch, and which furnished the waste to form a great thickness of sediments. The mountains and hills, formed by folding, by faulting, by warping, and by volcanic débris, inclosed basins and valleys in which the streams deposited the sediments obtained from the steep slopes of the higher lands. These sediments were deposited partly in lakes and partly in alluvial fans in front of the valleys which the streams had cut in the mountain slopes. The most important deposits, however, were laid down in flood plains, in deltas, and in swamps. From time to time the area of deposition shifted, because of the filling up of old basins or the warping of the land. Lakes were also in existence, the most famous being one in Wyoming in which the Green River formation occurs, consisting of impure limestone and thin, fissile calcareous shales, often as thinly laminated as paper. Between the leaves of these shales remains of plants, insects, and fishes are beautifully preserved, but no remains of mammals are found, except in the form of footprints. Since these sediments were deposited in more or less isolated basins, the work of correlating them with each other, and especially with the marine deposits of the Atlantic and Pacific, has been difficult.

The Eocene was an epoch of great coal formation, especially during the earlier portion (Fort Union). The great lignite deposits that cover one half of North Dakota were formed at this time, as were also extensive areas in Wyoming and Montana.

FIG. 529. — Map showing the probable outline of North America during a portion of the Eocene. The continental deposits are shown in solid black. (Modified after Schuchert.)

The Eocene was brought to a close by crustal movements of some importance which, on the Pacific coast, resulted in the draining of certain areas and the lowering of others to below sea level. In the same region some mountain ranges (Klamath) were again bowed up to some extent, and others (Coast Ranges) began their development. In the Great Plains region the changes were such as to bring about aggradation where degradation had formerly prevailed. The interior mountain region of the west was elevated and drained, and in subsequent epochs was not a region of extensive deposition. The eastern coast remained much as before. A narrow strip of land was added to both the Atlantic and Gulf coasts.

Eocene of Other Continents. — The evolution of the continents of Europe and Asia was not so far advanced at the beginning of the

Eocene as that of North America. Seas covered large areas that are now land, and there were probably extensive land masses which are now covered by the ocean. Europe was smaller than at present and at times was entirely separated from Asia by a narrow sea on the east side of the Ural Mountains. The most marked feature of the Eocene European continent was the greatly expanded Mediterranean Sea which, with its extensive arms, covered the sites of the conspicuous mountains of the present: the Pyrenees, Apennines, Alps, and Urals. Above the surface of this sea numerous islands probably stood on the sites of some of the ranges. The greater part of Spain seems to have been separated for a time from the mainland by a sea which also covered a portion of southern France.

Not only Europe, but Asia and Africa as well, were far from having attained their present outlines. The greater part of Africa north of the equator was under water, and an extension of the Mediterranean Sea reached to the Indian Ocean. Portions of Australia, New Zealand, Patagonia, and the West Indies were also submerged.

In portions of Europe and Africa a great thickness of limestone, made up of large Foraminifera (nummulites, p. 626), was deposited; besides which, an immensely thick mass of sandstone and shale which now outcrops on the Alps was also laid down. The nummulitic limestone was largely used in the construction of the pyramids of Egypt. The Eocene strata have since been raised to great heights, as is indicated by their presence on the Tibet Plateau at an altitude of 20,000 feet, in the Himalayas 16,000 feet above the sea, as well as high up on the Alps, Pyrenees, Caucasus, and other mountain ranges.

It will be seen from the above imperfect history that the outlines and mountainous regions of Europe and Asia were very different during the Eocene from what they are to-day.

OLIGOCENE

The Oligocene, which followed the Eocene, is sometimes included in the latter, but is usually separated from it because of the distinctness of the two series in Europe, and also because they can be readily separated in North America whenever fossils occur.

Atlantic and Gulf Coasts. — The Oligocene does not have a wide distribution on the Atlantic coast, but is well represented in the Gulf region, where 2000 feet of strata, rich in marine invertebrates, occur. The Oligocene in these regions rests upon the Eocene without a break, the two series being distinguished by a change in fauna. A great development of marls and limestone of this age in Central America and the West Indies shows that submergence was widespread in these regions. An island was raised in northern Florida early in the epoch which, by further arching of the sea bottom, became joined to the mainland in the Miocene.

Western Interior. — On the Great Plains region continental deposits of this epoch occur at various points from British Columbia to Mexico, and outcrop from two to three hundred miles east of the Rocky Mountains. They seldom rest upon the Eocene, but on the worn surfaces of the Upper Cretaceous, showing that while deposition was taking place in the mountain basins of the Eocene, the region of the Great Plains was an open, rolling country, traversed by streams which were degrading its surface. "A picture of the plains region in Oligocene times is that of broad, gentle, eastward slopes from the Rocky Mountains, plane or gently undulating and not mountainous, bearing broad streams with varying channels, sometimes spreading into shallow lakes, but never into vast fresh-water sheets. Savannahs were interspersed with grass-covered pampas traversed by broad, meandering rivers. This land was dry in dry seasons, but was flooded in very high-water periods. The materials were partly erosion products of the Rocky Mountains and Black Hills, such as true sandstones and conglomerates, but they include also fine layers of volcanic dust, wind-borne from distant craters in the mountains, far out on the plains of Nebraska and Kansas." (Osborn.)

Pacific Coast. — On the Pacific coast the Oligocene was an epoch of elevation and erosion, during which the land was not high except in a few places, as is indicated by the fine character of most of the sediments. The areas of deposition on what is now land were comparatively small.

Oligocene of Other Continents. — In general, the distribution of land and water was different in the Oligocene from what it was in the preceding epoch. One important transgression of the sea covered Germany and Belgium and at the time of greatest extension joined the North Sea with the Mediterranean and Aral seas. In France and Russia large areas were beneath the water. In the Paris basin the presence of salt and gypsum furnishes a clue to the climate during a portion of the epoch. In various parts of Europe (Germany, Switzerland, southern France, and Bavaria) extensive swamps were present in which were accumulated the lignite deposits that are now workable to some extent.

MIOCENE

The outline of North America was practically the same in the Miocene (Fig. 530) as in the Eocene, with the exception of the Mississippi embayment which was reduced in size, and the Florida peninsula which was formed later in the epoch.

FIG. 530. — Map showing the probable outline of North America during a portion of the Miocene. The continental deposits are shown in solid black. (Modified after Schuchert.)

Atlantic and Gulf Coasts. — On the Atlantic and Gulf coasts the strata rest — often unconformably — on the Eocene or Oligocene, and, in general, occur in a narrow, interrupted belt parallel to the older formations from Marthas Vineyard southward. The Miocene strata in some localities overlap the Eocene to landward, completely concealing it. The sediments on the Atlantic coast consist chiefly of sands, clays, and marls, with occasional beds of diatomaceous earth from 30 to 40 feet thick. In Florida, Georgia, and in the Gulf region limestones are the rule. The deposits of this epoch on the Atlantic and Gulf coasts are comparatively thin, being only 700 feet thick in New Jersey, 400 in Maryland, and even less in North Carolina.

Economic Products of the Miocene. — The economic products of the strata of this time are the phosphates of Florida, the oil of Louisiana, and the diatomaceous earth of the Atlantic coast.

Diatomaceous earth resembles chalk in color, but is lighter in weight, and, since it is composed of silica, does not effervesce with acids. On account of the hardness of its constituent parts and its extreme fineness, it is used as a base in the manufacture of preparations for cleaning and polishing silver, nickel, etc.[1] Since it is porous, it has been used as an absorbent for nitroglycerin in the manufacture of dynamite. It is also used as a non-conductor of heat.

The valuable *phosphate deposits* of Florida are believed by some investigators to have originated by the leaching of guano, or bone beds, and the deposition of the phosphate in the underlying limestone, either by precipitation in the pores of the rock or by replacing the limestone molecule by molecule. The phosphate may, however, have been disseminated through the beds in small quantities and later concentrated as the more soluble limestone was dissolved and carried away.

Western Interior. — In the Great Plains region east of the Rocky Mountains, the conditions traced in the Oligocene continued, and were probably not unlike those now prevalent where the flood plains of the upper Paraguay, Amazon, and Orinoco rivers of South America are confluent. In this portion of South America is a region larger than that occupied by the Miocene deposits of North America, with all the conditions necessary for the deposition and present distribution of sandstones, clay, and conglomerates, together with the preservation of animal remains. North American Miocene formations are found from Montana into Texas, although largely covered to the south and east by later deposits. Sediments of this age occur also in Montana, Nevada, Colorado, Oregon, British Columbia, and Alaska.

A lake existed in Colorado at this time (Florissant) which is interesting because of the excellent preservation of many insects and plants in its deposits. It lay in a narrow valley in the vicinity of active volcanoes, whose numerous eruptions spread ashes over its surface, burying the insects and plants which had been carried into it.

Pacific Coast. — The restricted seas of the Oligocene on the Pacific coast were much expanded during the Miocene, although at no time, as will be seen by consulting the map (Fig. 530), was a large portion of what is now land in that region submerged. The southern portion of the Great Valley of California (San Joaquin) was beneath the sea early in the epoch (Vaqueros), and in this bay a great thickness of marine sediments, consisting of sands and clays with some conglom-

---

[1] Volcanic ash is also used for this purpose.

erates, was laid down. The variation in the lithological character of the deposits within short distances is believed to have been caused by the rather local elevation of land due to faulting and subsequent stream rejuvenation. The California earthquake rift (Fig. 275, p. 277) is first known to have been a plane of movement at this time. This early (Vaqueros) sedimentation was followed by the deposition of sandstone, volcanic ash, and limestone, and a great thickness of diatomaceous material (Monterey). "It was an age of diatoms. These small marine plants lived in extreme abundance in the sea and fell in showers with their siliceous tests to add to the accumulating ooze of the ocean bottom, just as they are forming ooze at the present day in some oceanic waters. It is well known that diatoms multiply with extreme rapidity. It has been calculated that, starting with a single individual, the offspring may number one million within a month. One can conceive that under very favorable life conditions such as must have existed, the diatom frustules may have accumulated rapidly at the sea bottom and aided the fine siliceous and argillaceous sediments in the quick building-up of the thick deposits of the Middle Miocene time, some of which are a mile through. These diatomaceous shales are the source of some of the richest petroleum deposits of California." (Arnold.)

During much of the early portion of the Miocene and continuing somewhat later, faulting, folding, and volcanic outbursts of considerable magnitude occurred. Great volcanoes were active from Washington and Oregon along the Pacific ranges of California, almost as far south as Mexico. During the middle of the period mountain building and great local deformations took place, the effects of which were felt from Puget Sound to southern California. Extensive faulting along the earthquake rift and other fault zones occurred, while in other regions, low, broad folds were formed. The combined result was the uplift of the Coast Ranges of California and Oregon to an altitude of several thousand feet. The Cascades of Washington were also increased in height. This stage of diastrophism was followed by subsidence (Upper Miocene), as a result of which the northern part of the Great Valley (Sacramento) was submerged and in it were deposited sands and clays and beds of diatoms.

By the close of the Miocene the Klamath and Sierra Nevada mountains were peneplained, the material derived from them having been deposited in the Great Valley and coastal belt of northern California, forming the thick Tertiary strata now found there. These strata are composed of 8000 feet of sediments, largely belonging to the Upper Miocene, as well as an equal amount from the earlier stages. Volcanoes had practically ceased to be active over a large portion of the territory, but were probably still in eruption in some localities. The Miocene deposits on the Pacific coast are much folded; and some are even overturned, being in marked contrast in this particular to those of the Atlantic and Gulf coasts, which are nearly in the position they had when first laid down.

In addition to the marine sediments just discussed, continental deposits, consisting of sands and clays with some iron and coal, were being laid down during the Lower Miocene in the northern part of the Great Valley. From the western flanks of the Sierra Nevadas auriferous gravels were carried down by the streams and dropped in their beds during portions of the period, producing the " deep auriferous gravels " (Fig. 359 *B*, p. 374) and later the " bench gravels," some of which, as now, were buried beneath streams of lava and beds of tuff.

Mountain Building. — Before the close of the epoch the upheaval of the Coast Ranges of California and Oregon and the Cascades of Washington occurred; the fault along the east of the Sierra Nevadas was made; the growth of the present Sierra Nevadas was begun and, as will be seen later, many of the great mountain ranges of the world were elevated. During this epoch, too, the plateaus of Utah and Arizona were raised so as to permit the Colorado River to begin the excavation of its great canyon. The rugged scenery so characteristic of the west is the result of elevation which, for the most part, began at this time.

Basis for Separation into Periods. — In the discussion of eras and periods attention has frequently been called to the fact that they were brought to a close by deformations, some great and some small, which produced mountain ranges, or raised or lowered large areas of the earth's surface. We have just seen, however, that one of the great times of mountain building occurred, not at the end of an era, nor the close of a period, but in the midst of an epoch. It should also be remembered that climatic and other changes thus produced had little effect on the contemporary life of the time. In other words, the separation of the history of the earth into chapters should be based, not upon the unconformities, however great, but upon the changes which the life has experienced. Fortunately, as should be expected, because of the effect of the physical conditions upon animals and plants, the sediments laid down during eras and periods are usually to be separated, not only by the rather sudden extinction of many species and the appearance of new ones, but by unconformities as well. The problem is not, however, a simple one. When, for example, a continent has been isolated for long ages, the animals and plants living on it may be largely of forms that belong to a previous epoch in other parts of the earth, just as in an age of electricity and cement some isolated Indian tribes are still living in the Stone Age.

Igneous Activity. — Perhaps no other period in the history of the earth since Pre-Cambrian times displayed such extraordinary volcanism as the Tertiary, and of the four epochs of the period, the Miocene was by far the most important in this particular.

It has already been seen that the great volcanic outbursts of the Pacific coast occurred during the Miocene — especially during the middle of that epoch — covering that region of North America with ash which furnished the material for a great thickness of sedimentary deposits. Not only on the Pacific coast, but perhaps in every state west of the Rocky Mountains, some evidence of the igneous activity of this time can be found. It was during this period that a great quantity of lava and ash was poured into the basin of the Yellowstone National Park. Some of the forests that were buried in the ash at that time were later petrified and have been partially uncovered by erosion. Seventeen such petrified forests, one above the other, may be seen in one section (Fig. 531).

Fig. 531. — Section of the north face of Amethyst Mountain, Yellowstone National Park. Seventeen or more successive forests were covered with volcanic ash and the logs petrified. About two thousand feet of strata are shown. (After W. H. Holmes.)

The greatest area of lava in North America covers a region of between 200,000 and 300,000 square miles in Washington, Oregon, Idaho, and California (Fig. 304, p. 311), and is known, from the exposures on faulted and tilted blocks, to have a maximum thickness of at least 5000 feet. By far the largest bulk of this was outpoured during the Miocene. This enormous mass of lava was built up by successive lava flows averaging about 75 feet in thickness. On the canyon walls some of the sheets are seen to be separated by old soil beds, showing that the former lava surface had been exposed to the action of the weather so long as to be disintegrated to great depths before the overlying lava was outpoured. Lake beds, in one case 1000 feet thick, also rest upon one sheet and are covered by another. Although the Snake and Columbia rivers have canyons that reach a depth of several thousand feet, they have not yet succeeded in cutting their way to the base, except where they encounter the summits of the mountains buried beneath the flood of molten rock, or near the margin of the flow where it is thinnest.

Near the edge of the lava plateau water is sometimes obtained from artesian wells, which have been sunk to the sheets of sand and gravel spread by rivers from the surrounding mountains upon the earlier lava flows whose surfaces were afterwards covered by late lavas. However, no water can be obtained in this way over large areas, because the porous lava permits the water to percolate down to great depths, where it appears as springs far down in the canyons. Because of the constant and uniform supply of water thus obtained, the volume of the rivers fluctuates less than in almost any other part of the continent.

Miocene of Other Continents. — The seas that overspread Germany and Belgium in the Oligocene were withdrawn during the Miocene, but those of southern Europe not only remained extensive, but were so increased in size as to make that region an archipelago. With the exception of bays in Portugal and France and the submergence of the low lands bordering the North Sea, the shores of western Europe appear to have extended further west than now. Southern Spain was joined to Africa, probably by a wide land connection, but was, in turn, separated from northern Spain by a strait. An important and extensive sea stretched from Vienna to the region of the Black and Aral seas.

The Miocene was an epoch of great mountain building in the Old World as well as in the New. The Alps were upheaved and reached nearly their present altitude at this time. The elevation which produced them excluded the sea and formed basins in which rested inland seas and lakes where were preserved a record of the terrestrial life of the time. The Apennines were reëlevated late in the Miocene; and the Caucasus, on which Miocene strata occur at altitudes of 6000 feet, also date from this epoch. The Himalayas were raised either at this time or in the Eocene.

Volcanism, so stupendous in North America at this time, seems to have been of little importance in Europe, although some of the movements appear to have been accompanied by igneous activity.

The presence of extensive Miocene beds in Australia, New Zealand, north Africa, and elsewhere tell their story of submergence.

PLIOCENE

Atlantic and Gulf Coasts. — With a few exceptions, the eastern coast of North America had practically the same position in the Pliocene (Fig. 532) as now. The Atlantic coast from New York northward extended farther out than at present; Florida was, for the most part, under water; and a very narrow belt along the Gulf coast from Florida to Texas and another in Mexico were submerged. This being the case, the conspicuous deposits are naturally those laid down upon the land, the marine sediments being now chiefly hidden from view beneath the sea. The comparatively wide distribution of these continental sediments is due in the first place to their recent age, and in the second place to the fact that some of them occupy sites of continued deposition, as, for example, in the Great Basin region. These deposits have an origin similar to those of previous epochs

FIG. 532. — Map showing the probable outline of North America during a portion of the Pliocene. The continental deposits are shown in solid black. (Modified after Schuchert.)

already discussed. Streams debouching from mountainous lands dropped their sediments upon reaching a low gradient, making alluvial fans and plains. On account of the reduction of their volumes through evaporation and seepage, the rivers developed great flood plains. Shallow lakes which existed at that time, formed either by warping or by the choking up of river channels by deposits of sand and gravel, were later filled with sediments.

Mention should be made of a series of deposits (Lafayette) of Tertiary age, the exact status of which is yet in doubt (formerly supposed to be Pliocene, but some of which are Oligocene) which have an extensive distribution, occurring in many places on the Atlantic and Gulf coastal plains in the southern portion of the Mississippi Valley up to southern Illinois, and in the valleys west of the Appalachians. This formation (Lafayette or Orange Sand) commonly has a thickness of 20 to 30 feet, and is composed of gravel and sand in the lower Mississippi Valley and of clay and silt over large areas of the uplands east of the Mississippi River. It was derived from the insoluble residue of older formations and consists of chert, quartz pebbles, and other insoluble materials. The color varies, but is often red, orange, or yellow. This deposit was, probably, formed as follows. The peneplanation and subsequent weathering of the land surfaces during the early stages of the Tertiary produced a layer of loose, insoluble material. In the Oligocene an upwarping along the axis of the Appalachians began and increased during the epoch. As a result, the rejuvenated streams carried much detritus and dropped a part of it upon reaching the lower lands. With the continued rise of the mountain belt and adjacent regions, the streams removed the sediments first laid down, and redeposited them farther downstream. The sands and gravel deposited not only filled up the lower portions of the valleys, but also, to some extent, covered the former divides. At present, much of the formation has disappeared in regions of strong erosion and, seaward, is more or less concealed by younger beds. In some places it caps divides but is absent from the valleys.

The marine deposits have a very limited distribution on the east coast and are of little thickness, being most important in Florida.

Western Interior. — The Pliocene deposits of the western interior are widely scattered and of limited extent. Beds of this epoch have been recognized in Kansas, Nebraska, Oregon, and the Staked Plain of Texas. As already stated, it is probable that much of the Great Basin and other regions is underlain by Pliocene deposits.

Pacific Coast. — Deposits of this age are less widespread on the Pacific coast than those of the Miocene. A change from marine to fresh-water conditions in a portion of the area may have been due to a raising of the land near the coast, or to an elevation along faults which excluded the sea. Volcanic activity took place during the period in certain portions of northern and central California, and in the Sierra Nevadas and Cascades.

Pliocene Elevation. — The deformation of the peneplain of the Appalachian region raised the Coastal Plain and shifted the coast line to the east, except in Florida, where there was a slight depression. It is possible that during this period of elevation the now submerged valleys of the St. Lawrence, Hudson, Delaware, and Mississippi were eroded.

The plateau region of the west was uplifted at various times prior to the Pliocene, during that epoch, and later, and has since been intrenched to form the great canyons for which it is famous.

Near the close of the Pliocene the Rocky Mountains and the Sierra Nevadas began a period of growth which has given them their present altitude. Instead of folding, as at the close of the Mesozoic, the elevation was chiefly due to warping and faulting. A study of a cross section of the Sierra Nevadas brings out the fact that the slope on the west is long and gradual and deeply intrenched by such great valleys as the Yosemite and Hetch Hetchy, while on the east it is very abrupt and short. This marked difference in the eastern and western slopes is due to a profound fault on the east, which was first formed in the Miocene, along which an enormous block was raised and tilted to the west, leaving its eastern edge to form the crest of the range. The movement along the fault plane has apparently not yet ceased, as is shown by a slip of 25 feet which occurred in 1872. The raising of the Sierra Nevadas inclosed the Great Basin region, shutting off the moist winds of the Pacific and making it a desert.

During the Pliocene the Cascade Mountains seem to have been peneplained, the mountain mass being raised shortly before or after its close. The rugged scenery of these mountains is the result of comparatively recent erosion. Volcanic activity continued in the epoch and became marked at the end, many of the great volcanoes of the west dating from the close of this epoch, or later.

The close of the Pliocene was a time of widespread elevation, the outline of the continent being extended, with few exceptions, farther out than now. So marked was this elevation that for many years it was generally believed to have been the cause of the accumulation of ice which resulted in the Glacial Period.

High Plains and Bad Lands. — The great sheets of clay, sand, and gravel which during the Tertiary were burying the eroded surface of the Upper Cretaceous and other rocks in the region east of the Rocky Mountains, gradually built up a great plain, in some places 500 feet thick, stretching from the foothills of the Rocky Mountains for hundreds of miles. This is known as the High Plains region. The deposition that formed the Great Plains was not continuous in any one place throughout the period, but shifted from time to time, being local and contemporary with more or less erosion. Eolian deposits (loess) were building up the level, grassed surfaces (as, indeed, they are to-day) and constitute a not inconsiderable part of the formation. In recent times, however, erosion has been in excess of aggradation, and the plain is being cut away. Uneroded remnants of this plain, remarkable for their level surfaces, remain in western Kansas, Nebraska, and westward.

Where the plain has been dissected by canyons and ravines, it is seen to be composed of unconsolidated gravels, sands, and clays. Since the region has a scanty rainfall, although with occasional heavy downpours (cloud-bursts), vegetation, except on the level surfaces of the plain, is sparse. The scantiness of the vegetation on the sides of the ravines, combined with the looseness of the sediments of which the country is built, affords conditions most favorable for rapid erosion when the torrents of water from the occasional heavy rains rush down the ravines. As a result, in certain places along the edges of the High Plains we find a maze of hills and ravines (Fig. 533) with almost no vegetation except on the tops of the mesas (the remnants of the former surface). These are the "Bad Lands," "Mauvaises Terres" of the early French explorers, and constitute a scenery as weird as any on earth.

Pliocene of Other Continents. — The emergent condition of Europe during the Pliocene was in contrast to the widespread seas of the previous epoch. In the north of Europe, with the exception of Belgium and a little of northern France, the seas had withdrawn. Great Britain, as throughout the early epochs of the Tertiary, had a greater land area than now, since only a small portion of the southern part was beneath the sea at this time, while England, Ireland, and Scotland were probably connected; and the northern coast extended farther out than now.

FIG. 533. — The Bad Lands of South Dakota. (Photo. E. H. Barbour.)

The Himalayas were being eroded during the Pliocene; and thousands of feet of sandstones and conglomerates were deposited at their foot before its close, some of which, however, were laid down in the later Miocene. In South America the coasts of Argentina and Patagonia were submerged, and the last upheaval of the southern Andes was accomplished at this time.

REFERENCES FOR PALEOGEOGRAPHY

BLACKWELDER, E., — *Regional Geology of the United States of North America*, pp. 39–46.
OSBORN, H. F., — *Age of Mammals*, pp. 84–93; 182–184; 244–246; 304–306.
SCHUCHERT, CHAS., — *Paleogeography of North America:* Bull. Geol. Soc. America, Vol. 20, 1910, pp. 597–600.
WILLIS AND SALISBURY, — *Outlines of Geologic History*, pp. 200–264.

LIFE OF THE TERTIARY

Rise of Mammals. — In the present imperfect state of our knowledge of the life at the beginning of the Cenozoic, it is, perhaps, even more difficult to account for the presence of highly developed mammals, as soon as the reptiles became extinct, than to account for the disappearance of the latter.

It is improbable that the mammals on the earth to-day were descended from any of the mammals whose remains have been found in the later Mesozoic rocks. Indeed, it is even doubted that the true (Eutheria) mammals were descended from the marsupials (Metatheria) mammals. Two theories are offered to explain their sudden appearance. (1) The first postulates their existence in some isolated country, in the Arctics whose climate was not cold at that time, or elsewhere, for a long period of time during which they had been developing along different lines, but from which they were prevented from spreading because of some barrier to their movement, either water or mountains. When this barrier was removed, the mammals deployed over the world, and finding the new conditions favorable for their existence, rapidly took the place in nature formerly occupied by the reptiles. (2) The second theory (p. 549) is based upon the supposed existence of mammals on the uplands of the Mesozoic. Since practically all of our knowledge of the life of that era is obtained from coastal swamp and delta deposits in which almost no forms of life are found except those which frequented marshes, little is known of the life of the higher and more extensive areas of the earth's surface. It is to be noted, too, that the very earliest Tertiary upland deposits contain a rich mammalian fauna. It does not seem improbable, therefore, that on the higher land of Asia and North America mammals of considerable variety were in existence during the later days of the Mesozoic; all proof of which has either been lost by the wiping out of the upland deposits by erosion, or else has not yet been discovered.

Archaic Mammals of Ancient Ancestry. — In the earliest known Eocene beds (Puerco) the remains of small, archaic mammals (marsupials) associated with true mammals (Eutheria) occur, which clearly belong to animals whose ancestors lived in the Mesozoic, some of which (Plagiaulacidæ) date back even to the Upper Triassic. These animals are characterized by large grinding teeth (Fig. 534) with many elevations (multituberculate), and elongated front teeth (incisors); the latter being, in some cases, chisel-shaped, as in the rabbit, and in others pointed. The "back teeth" of the lower jaw are, moreover, usually very different from those of the upper jaw. These animals were all small or of moderate size, the largest known having about the bulk of a beaver. Judging from the teeth, it seems probable that some were gnawing animals like rabbits or mice (but not true rodents), and that others were either fruit eaters (frugivores) or even insect eaters (insectivores).

Fig. 534. — An archaic mammal, *Ptilodus* (Upper Cretaceous). (After Gidley.) The many-ridged teeth are especially to be noticed.

This entire class became extinct before the close of the Eocene and should be considered as survivors from the Mesozoic, which lingered for a time in the Tertiary. The question naturally arises as to the cause of their extinction, since they were able to survive the many changes, not only of the Mesozoic, but of those at the close of the era as well. If the variety of their fossils in the Mesozoic formations indicates the relative abundance of these archaic mammals as compared with other forms during the era, conditions of climate or of food, or competition with the dinosaurs must have prevented their increase. If competition with the dinosaurs prevented their increase in the Mesozoic, it would have been surprising had they been able to compete with the true mammals which appeared in the Eocene. Although mammals, they were lowly in organization; and, even in the Upper Cretaceous where the vegetation was of the modern type, they were not abundant.

Amblypoda (Greek, *amblus*, blunt, and *pous*, foot). — Along with other true mammals associated with the above archaic ones of

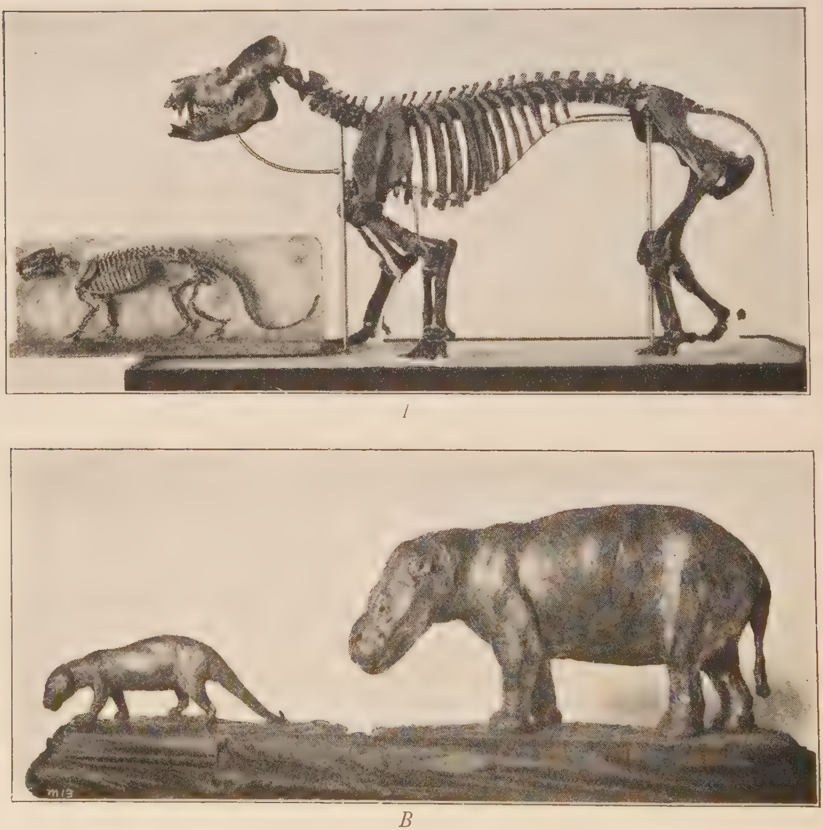


Fig. 535. — Skeleton and restoration showing the evolution of the amblypods in the early Eocene. (Models by C. R. Knight, under the direction of Prof. H. F. Osborn.)

Mesozoic type, there appeared a group of heavy creatures (Amblypoda), with stout limbs ending in stumpy, five-toed feet. These amblypods (Fig. 535 *A*, *B*) were conspicuous in North America during the Eocene but became extinct before its close.

The early representatives (Fig. 535) had few distinguishing characters except their heavy build, but before the extinction of the race, some of them (Eobasileus) not only took on greater bulk, attaining elephantine proportions, but also developed a peculiar head (Fig. 536), the most conspicuous features of which were the three pairs of knobs, or horns, and the long, saberlike teeth (canines) which projected several inches below the upper jaw. One pair of the knobs was situated on the nose, a larger pair over the eyes, and the third pair above the ears at the back of the skull. It is not known whether the protuberances were covered with horn or with callous skin, but it was probably the latter. The use to which the long, saberlike (canine) teeth, possessed by both males and females, were put is not definitely known, but it seems probable that they were used to pull down branches from the trees, and that the leaves were then stripped off into the mouth by a rapid side motion of the head. The brain was smaller in proportion to the bulk of the animal than in any other mammal, living or extinct, an animal weighing two tons having a brain no larger than that of a dog. Moreover, the brain was smooth, and a large proportion of it was formed of the lobes of smell (olfactory). These animals seem to have reached the climax of brute mass as compared with brain power on the mammalian stem, and are to be compared with the massive, small-brained dinosaurs of the reptilian stem. At certain times they were very abundant, as is shown by the fact that two hundred more or less complete skeletons have been collected by one museum alone.

Fig. 536. — The most highly specialized of the amblypods, *Eobasileus* (Upper Eocene). (After Professor Osborn.)

The Lower Eocene amblypods were simpler in some particulars than the later ones, being smaller and hornless, with shorter canine teeth, although the grinding teeth differed very slightly from those of their massive descendants. In other words, aside from increase in size and the ornamentation of the skull, the evolution of the race was slight.

It is interesting to speculate on the causes of the extinction of this race which may have had an existence of more than a million years. Its fate may have been due to two causes: (1) to the small size of the brain, and (2) to the poorness of the grinding teeth which were no more efficient in the huge forms towards the close of the period than in the earlier and smaller species. The low brain power was of disadvantage to them in their competition with other forms and also gave them little ability to protect their young from the more crafty carnivores. Bulk is a disadvantage under changing conditions (p. 550) and may alone have been responsible for the disappearance of the race. This great order was one of the many which, for a time, took a prominent place among the animals of the world, but which after a long span of life disappeared, leaving no descendants.

REFERENCES FOR AMBLYPODA

Chamberlin and Salisbury, — *Geology*, Vol. 3, pp. 232–233.
Hutchinson, H. N., — *Extinct Monsters and Creatures of Other Days*, pp. 249–260.
Scott, W. B., — *A History of Land Mammals in the Western Hemisphere*, pp. 443–451.
Woodward, A. S., — *Vertebrate Paleontology*, pp. 292–299.

Ancestors of the Carnivores. — The earliest Eocene carnivores (Creodonta) are so generalized (*i.e.*, combine characters now possessed by widely different groups of animals) that it is difficult to tell even to what order they belong. Their teeth are rather better adapted for cutting food than for grinding it (none, however, have sectile teeth, perfectly adapted for flesh eating); and their toes are provided with curved nails that are rather clawlike but are not the sharp, retractile claws such as are possessed by the cat to-day. These creatures were descended from others whose feet were even more

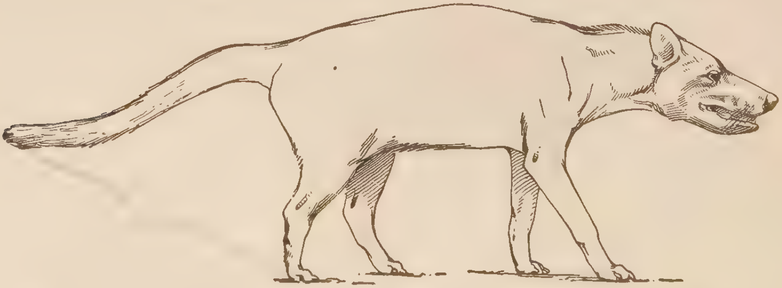


Fig. 537. — A primitive carnivorous mammal, *creodont* (Middle Eocene). (After Professor Osborn.)

generalized, which also gave rise to the hoofed mammals, such as the horse, elephant, and ox. They were, in other words, mammals with such indefinite characters that, by the modification of their organs, their descendants could be developed into animals widely different in form and habits, such as the lion and the dog, the seal and the whale. Some of the members of the generalized carnivores (Creodonta) were larger, others smaller, than a fox. The largest form of the Eocene (Pachyæna) was the size of a small bear and had unusually blunt teeth, which are thought to indicate that it lived on decaying flesh.

These primitive carnivores (Creodonta) (Fig. 537) lived through the Eocene into the Oligocene, when they became extinct. Those that passed into the latter epoch attained not only their greatest bodily size, but their greatest brain capacity as well. This bears out the general rule that the brains of surviving races are, upon the whole, larger than those of declining races. However, we shall find in our later study that certain tribes with well-developed brains, as for example certain rhinoceroses (Teleoceras) and elephants (Mastodon), failed to survive. The reason for such extinction is usually, though not always, to be found in the failure of other organs to develop to meet new conditions.

Marine Mammals. — Perhaps nothing shows the rapid evolution of mammals in the Tertiary better than the appearance early in the Eocene of whales perfectly adapted to marine existence, which were not descended from the marine reptiles of the Mesozoic, but from land mammals. Whether mammals gradually acquired an aquatic habit because of the abundance of fish which they voluntarily and habitually sought, or whether they were forced to find new food on account of the competition on the land, it is not possible to state (see also marine reptiles, p. 552), but probably in the one way or the other, whales, porpoises, sea lions, and other animals arose. These marine mammals were not descended from a common ancestor, but some (manatee) are thought to have been derived from the same stock as the elephant, some (whales) from carnivores, and some (seals), possibly, from the same stock as the bear.

Zeuglodon. — For many years enormous vertebræ have been found in the Eocene deposits of the Gulf coast, the largest of which measure 15 to 18 inches in length and weigh 50 to 60 pounds in the fossil condition. They belong to marine mammals to which the name Zeuglodon (Greek, *zeugle*, yoke, and *odont-*, tooth) has been given because of the double-rooted back teeth which present the appearance of a yoke. The head of Zeuglodon was, in some cases, 4 feet long, the length of the body 10 feet, while the tail was 40 feet long. The animal (Fig. 538 *A*, *B*) was comparatively slender, an individual 50 to 60 feet long having a thickness of only 6 to 8 feet. The teeth are very unlike those of the primitive mammals, having been modified for grasping and cutting. Back of the head were two short paddles not unlike those of a fur seal, but the hind limbs were so reduced that they were retained within the skin.

Fig. 538. — Skeleton and restoration of *Zeuglodon*. (Skeleton

The zeuglodonts were divers and probably lived upon squids, as do the sperm whales to-day. The advantage of such a long tail in proportion to the rest of the body has led to two suggestions: (1) with it the animal could move at great speed through the water, perhaps 20 to 30 miles an hour; and (2), as far as definite evidence shows, the tail may have been used quite as much for the storage of fat as for propulsion.

The ancestry of the zeugolodonts has been traced back to a small whale (Protocetus) with a skull about two feet long, in which the teeth show a surprising resemblance to those of primitive carnivorous land mammals (Creodonta). This whale has the typical number of teeth (44) with one, two, or three roots, the dogteeth (canines) projecting beyond the others. Following these whales came others (Eocetus) differing from those last described, in the fine, saw-edged teeth. Probably descended from these (Eocetus) are others (Prozeuglodon) in which the teeth depart widely from those of land mammals and closely approach those of its most specialized descendant, Zeuglodon. It is thus seen that the Eocene whales were not descended from the Mesozoic marine reptiles, but from the land mammals, just as the ichthyosaurs and mosasaurs (p. 555) were

after Gilmore, and restoration modified after Osborn.)

descended from land reptiles. The specialized zeuglodonts constitute a side branch and are not true whales. They became extinct before the close of the Eocene.

Ancestors of Existing Whales. — The earliest known ancestors of modern sperm whales are believed to have been small, Eocene marine mammals (Microzeuglodon), whose modified descendants in the Miocene have been called "shark-toothed" whales because they had teeth somewhat similar in appearance to those of a shark. The Miocene whale differs from its Eocene ancestor (Microzeuglodon) in the number and simplicity of the teeth and in the skull, which resembles that of existing toothed whales. With these Miocene shark-toothed whales (Squalodonta) begins an almost unbroken series which leads to the sperm whale. By one investigator it is stated that the evolution from the shark-toothed whale to the sperm whale is sudden and almost "explosive," the entire evolution being completed in a very small section of the geological time of the Upper Miocene. Dolphins and whalebone whales are known only from the Miocene, but probably date from an earlier epoch. Sea cows (Eosiren) are mingled with the remains of zeuglodonts in the Eocene deposits of Africa.

REFERENCES FOR MARINE MAMMALS

Abel, O., — *The Genealogical History of the Marine Mammals:* Smithsonian Rept., 1907, pp. 473–496.
Beddard, F. E., — *The Book of Whales*
Beddard, F. E., — *Mammalia.*
Lucas, F. A., — *Animals of the Past,* pp. 58–64.
Osborn, H. F., — *Age of Mammals,* p. 171.

Ancestors of the Hoofed Mammals (Ungulates). — Interest in the Eocene centers not so much upon such groups of animals as the Amblypoda, which, though the largest and most conspicuous of their time, left no descendants, as upon those animals that are either actually the ancestors of recent mammals or so closely related to them that they help us to understand the evolution and past history of the mammals living to-day.

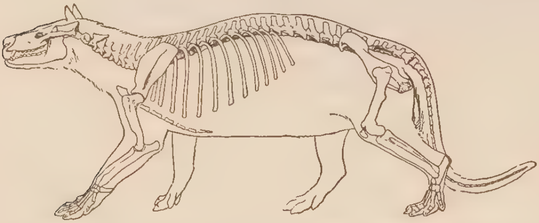


Fig. 539. — *Phenacodus*, an Eocene mammal which in many particulars is like the ancestor of the hoofed mammals or ungulates. (After Scott.)

Some of the earliest Eocene herbivorous mammals (Condylarthra) are so generalized that many groups seem to converge in them, even the carnivores and herbivores not being easily distinguishable. These ancestral herbivores were small or of moderate size and walked flat on the foot (plantigrade) and not on the toes (digitigrade), as do the horse and cow. The ends of the toes were not quite in the form either of hoofs or of claws. One of the best known forms (Phenacodus) (Fig. 539), although not the direct ancestor of any of the modern mammals, is of great interest since it probably differed but slightly from those in the direct line of descent. It resembles the carnivores in having an arched back, strong legs, and five toes on its feet. It walked somewhat on its toes and the toes ended in a flat "nail" which may be considered as the beginnings of a hoof. The teeth were short-crowned (that portion of the tooth above the jaw being short) and comparatively simple, showing that their possessor was omnivorous in habit. The head is remarkably small and the nearly smooth brain is small, even for a head of this size. It apparently had no means of defense and sought safety in flight. Some species of the genus attained the size of a sheep.

It was from some such animal, so simple in structure that it might almost equally well be ancestral to the carnivores (the dog and lion) and to the hoofed mammals (ungulates, — horse, ox, camel), that the modern hoofed mammals, such as the horse, ox, rhinoceros, and elephant are descended. It is interesting in this connection to note that Huxley and Cope had independently pictured what the ancestors of the hoofed mammals would be like when discovered. This prophecy was fulfilled in the finding of Phenacodus, although the animal has proved not to be directly ancestral to any form, but rather to stand as a type.

REFERENCE FOR PHENACODUS

SCOTT, W. B., — *A History of Land Mammals in the Western Hemisphere*, pp. 456–458.

Divergence of the Even and Odd-toed Hoofed Mammals (Ungulates). — The common herbivorous mammals[1] of the present are separated into two great divisions, those with a cloven hoof (Fig. 540), the even-toed ungulates (Artiodactyla), such as the pig, deer, and camel, and those with a large central toe, the odd-toed ungulates (Perissidactyla) (Fig. 541), such as the horse with one toe, the rhinoceros with three, and the tapir with four toes on the fore foot and three on the hind foot. The five-toed ancestors of the earliest Eocene had already developed feet that gave promise of odd-toed and even-toed descendants; even Phenacodus, the most generalized of the early mammals, has a foot in which the central toe is rather larger than the others, and should be placed in the division of odd-toed ungulates (Perissidactyla).

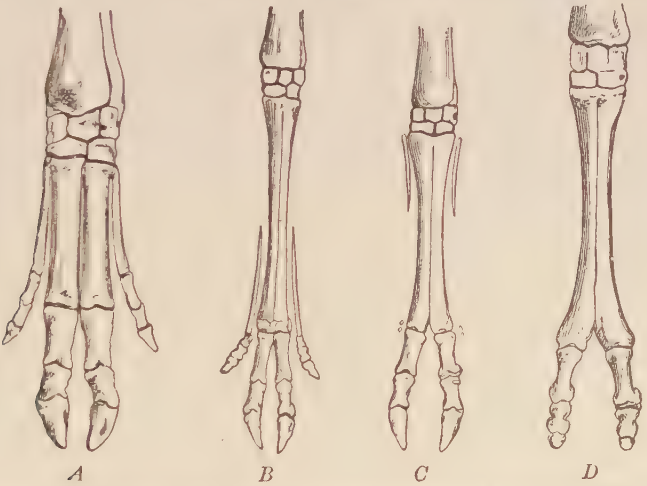


FIG. 540. — Evolution of the foot of even-toed mammals (artiodactyls); *A*, hog; *B*, roebuck; *C*, sheep; *D*, camel.

---

[1] The Proboscidea (elephants) constitute a third great group of hoofed animals with five-toed feet.

It will readily be seen that, if the weight of the body rested principally upon the middle or third toes, and if the animal raised the heel from the ground, the thumb or first finger would not ordinarily touch the ground; and if this habit of walking on the toes became better developed in successive generations, not only the first toe but the fifth as well might become of no use to the animal and might finally atrophy. A continuation of the process, accompanied by a lengthening of the foot, would result in the dropping of the second and fourth toes and in the formation of the highly specialized, one-toed foot of the horse (p. 608).

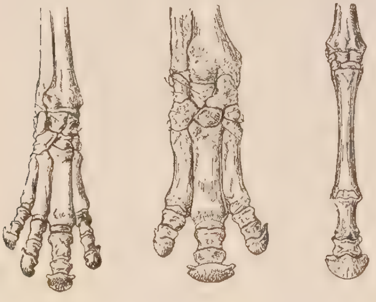


Fig. 541. — Evolution of the foot of odd-toed mammals (perissidactyls), illustrated by existing families: *A*, tapir; *B*, rhinoceros; *C*, horse. (After Beddard.)

If the weight, instead of being directly on the middle toe, was *between* the third and fourth toes, a more digitigrade habit (walking on the toes) would result in the reduction and later dropping of the thumb or first finger, leaving a four-toed foot. By the further reduction in size of the side toes, a foot like that of a pig, with two strong toes and two small ones, would result. When these side toes disappeared, the animal had but two toes on each foot, like the camel and sheep. Judging from the abundance of the even-toed ungulates (artiodactyls), it seems that, as a whole, this type of foot has proved to be the best. These modifications in foot structure apparently were the result of a change from the forest conditions of the Eocene, where soft ground and succulent vegetation were the rule, to the plains vegetation (p. 630) of the later times, with their siliceous grasses where a short, spreading foot would not give the animal the speed necessary to move long distances in a short time, for food and water (p. 610).

Factors in the Evolution of Mammals

In the course of the history of the mammals to be studied it will be found that, beginning with some such ancestor as Phenacodus, which is full of mechanical imperfections, the skeletons were modified chiefly in four particulars, each of which was of more or less vital importance to the various races affected.

(1) That race was more likely to survive whose members had teeth enabling their possessors to grind up nutritious food, no matter how tough and hard. Particularly was this true if the teeth of successive generations developed better grinding surfaces, permitting their possessors to take advantage of new food or food that, because of inability to grind it, was unsuited to their ancestors. The efficient grinding teeth of the horse, cow, and elephant, as will be seen, are the result of such an evolution.

(2) Since the swiftest animals are more likely to escape their enemies, those that possessed limbs constructed for rapid motion were most likely to survive. The leg best suited for this purpose is one in which the foot is lengthened, the joints perfected, and the number of toes reduced. The one-toed horse may be considered the climax of such evolution.

(3) Since more sagacious animals are better able to find food, escape their enemies, and care for their young, it naturally follows that those with large brains (Fig. 542) were more likely to survive. As the various races of mammals are discussed, attention will be called to the increase in the size of the brains, and any exceptions will be noted.

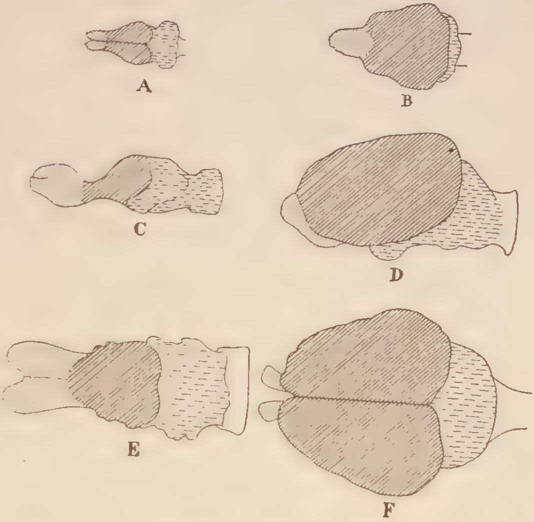


Fig. 542. — Brains of ancient (on left) compared with modern (on right) mammals: *A*, creodont; *B*, dog; *C*, early amblypod; *D*, rhinoceros; *E*, highly developed amblypod (*Uintatherium*); *F*, hippopotamus. Olfactory lobes (dots), cerebral hemispheres (oblique lines), cerebellum and medulla (dashes). (After Osborn.)

(4) Increased bulk and the strength which usually accompanies size is often a protection against enemies and, in the case of males, results in the destruction of the smaller and weaker members of the same species. As a consequence, it will be seen that the surviving species of a given order often become larger in the course of their

history. The disadvantage of great size has been discussed (p. 550).

Mammalian Teeth. — The typical or ancestral number of teeth is 44, a number which is seldom found in living forms, since some have been developed at the expense of others and some have been dropped. It is seldom that a larger number occurs. (The porpoise has 246.) The primitive type of grinding teeth (molars), from which the highly perfected teeth of the present carnivorous and herbivorous mammals were derived, had a grinding surface merely roughened by three sharp-pointed cones arranged in the form of a triangle (tritubercular). From a tooth of this simple type has been developed the complicated and efficient grinders of the higher herbivores (Fig. 543). Another notable change, in such races as the horse and the elephant, has been the lengthening of the tooth, adapting it to the nutritious grasses (p. 610) of the dry, sandy plains.

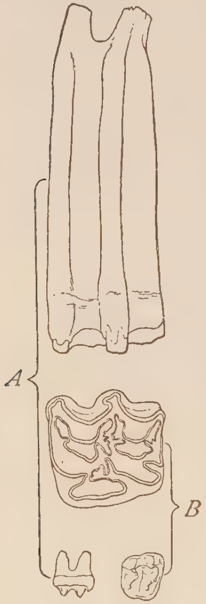


Fig. 543. — Corresponding grinding teeth of *Eohippus* (below) and the modern horse (above). The relative size and efficiency are shown. (After H. F. Osborn, *Age of Mammals*.)

Feet. — The primitive foot (p. 598) is five-toed with the sole resting flat on the ground. From such a foot, the extremely effective one of the higher hoofed, herbivorous mammals was developed. This was accomplished (1) by the raising of the ankle and wrist joints which lifted the first and fifth toes from the ground so that these toes became useless, and degeneration set in which eventually, as in the case of the horse, caused all except the middle toe to disappear. (2) In the primitive foot the joints of the wrist and ankle were loose, but they became more efficient by the development of the "tongue and groove" structure which very effectively prevented lateral movement. The change, in general, has been from a loose-jointed limb with "ball-and-socket" joints, to one with keeled joints; from walking with the sole of the foot flat on the ground (plantigrade), to walking on the toes with the heel well elevated above the ground (digitigrade); from a five-toed foot to one with a smaller number of functional toes. It should not be forgotten, however, that along with races that were changing in structure, there lived others that have been little modified.

The feet of the carnivores seldom show a reduction in the number of toes. This is due to the fact that, since the foot must be adapted for both rending and tearing, as well as for locomotion over both rough and smooth ground, it would not be of advantage to the animal to have the number of toes greatly reduced. The principal changes from the primitive carnivores (creodonts) (Fig. 537) to the modern forms, as far as foot structure is concerned, have been in the perfection of the joints, in the more digitigrade habit of walking (walking on the toes), and in the formation of sharp, retractile claws.

Limits to Evolution. — There is a limit to evolution after fundamental modifications in the structure have occurred. For example, thus far no mammal is known to have been transformed from an aquatic to a land type, although numerous examples of the reverse are known. No swift-moving types have retrogressed into slow-moving forms. Animals adapted to tree life, however, are believed to have taken on terrestrial habits and to have become modified to fit them.

Lost parts are never reacquired; as, for example, if the number of toes of an animal is reduced, its descendants never have more than the minimum number possessed by its ancestors. Each part that is lost, such as a tooth or a digit, narrows down the possibility of future changes in structure to meet new conditions. A specialized organ can never again become generalized. It will readily be deduced from the above that animals highly specialized to meet certain conditions will be more likely to fail to meet changed conditions than those that have a more generalized structure.

REFERENCES FOR THE EVOLUTION OF MAMMALS

Osborn, H. F., — *Age of Mammals*, pp. 18–35.

Scott, W. B., — *A History of the Land Mammals in the Western Hemisphere*, pp. 645-655.

Odd-toed Mammals (Perissidactyls)

This division of the mammals was in the past more important than at present, being now represented by the elephant, tapir, and horse.

Titanotheres (Greek, *titan*, a giant, and *therion*, a beast). — Of the many families that, for a time, gave promise of permanence and later became extinct, none is more interesting than the titanothere, a tribe distantly related to the rhinoceros, which is first known in the early Eocene (Wind River) and became extinct with apparent suddenness in the early Oligocene (White River), just as it had, perhaps, reached its greatest abundance and variety.

Two groups of titanotheres are represented in the Lower Eocene near the beginning of the history of the race; one abundant genus (Lambdotherium) had slender limbs and was capable of swift movement, indicating that it was adapted to the open basins of the mountain regions; and the other (represented by Eotitanops) was composed of larger and stockier animals, ancestors of those in the Oligocene, that grew to be about two thirds the size of a tapir. The largest, as well as latest, forms (Brontotherium) were awkward creatures with an elephantine body but with legs less massive than those of an elephant. The head (Fig. 544) was saddle-shaped, with a pair of large horns, placed side by side and branching off from the end of the nose, and which were probably covered with a callous skin. The brain was not larger than the fist of an average

FIG. 544. — Evolution of the *titanotheres*. (After Scott.)

man. They belong to the odd-toed division of mammals (perissidactyls), with four toes on the fore and three on the hind foot, the larger middle toe of the fore foot showing that, like the living tapir, the titanotheres belonged to the odd-toed division of mammals.

No sooner had the titanotheres reached the climax of their evolution than, with apparent suddenness, they became extinct. This is well shown in the Oligocene deposits of the Bad Lands of South Dakota (p. 588), where they are magnificently represented and undergo their entire final evolution and extinction during the time taken in the deposition of the 200 feet of sediments in which their remains are embedded. (Osborn.) The bulk and specialization of the animals rendered them more liable to extinction, since they were at a disadvantage with the smaller and more active true rhinoceroses of similar food habits which were, perhaps, able to make longer journeys between water and feeding grounds. To this should be added a growing scarcity of food, emphasized by drought at certain seasons. It is not improbable that the competition with the camels and other swift-moving forms with teeth better adapted to the conditions may have been an important factor in causing the scarcity of food which was fatal to the huge titanotheres, although not so to the less bulky rhinoceroses.

From the Oligocene on, the swifter, grazing forms tended to replace the slow-moving, browsing (feeding on the leaves of shrubs and trees) forms, although some, such as the rhinoceros, have survived to the present.

REFERENCES FOR TITANOTHERES

HUTCHINSON, H. N., — *Extinct Monsters and Creatures of Other Days*, (*Brontops*), p. 261.

OSBORN, H. F., — *Age of Mammals*, pp. 134, 239–240.

SCOTT, W. B., — *A History of Land Mammals in the Western Hemisphere*, pp. 308–319.

Rhinoceroses. — The history of this great, odd-toed, hoofed (perissidactyl) family illustrates two points to which attention will be directed in the discussion of other families: (1) the presence in abundance in North America of members of a family that has long since been extinct in the western hemisphere but is still living elsewhere, and (2) the evolution of a number of side branches, differing widely in structure and habits. The rhinoceros family is now confined to Africa, southern Asia, and a few of the large islands of the Indian Ocean, but in the Oligocene and Miocene not only did rhinoceroses that are ancestral to existing genera live in North America, but a number of side branches were also developed on that continent which differed widely from those of to-day, some of which lived, at least locally, in great abundance. In a remarkable deposit of the Lower Miocene (Harrison Beds, near Agate, Nebraska) a slab of rock 10 feet by 40 feet by 18 inches was uncovered by an American Museum party in 1912, in which are 75 skulls of a species of rhinoceros (Diceratherium), together with the bones of these and other mammals. This deposit is without doubt exceptional, but nevertheless shows that, in certain localities, these rhinoceroses were extremely abundant. In the Oligocene of North America three branches of the family are known, but in the Miocene they had evolved into a number of branches, which, however, may be united into three groups.

(1) One of these may, for convenience, be called the "swimming rhinoceros" because of the spreading, four-toed foot which was doubtless an efficient organ for swimming. This branch (Metamynodon) was apparently semi-aquatic and was fitted for life in the lakes and rivers of the Oligocene. It was stout and rhinoceros-like in shape, the eyes were placed high on the head, and the nostrils opened upward so that it could breathe when the head was partly submerged. Its canine teeth were elongated into tusks and were doubtless used for uprooting the plants from the bottom and banks of the lakes and rivers which it frequented.

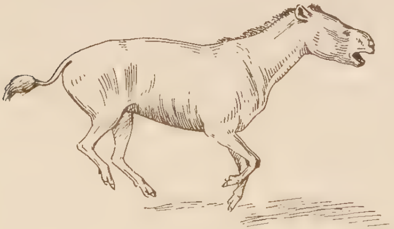


Fig. 545. — A running rhinoceros (*Hyracodon*) showing the modification of structure for plains conditions. (After Prof. H. F. Osborn.)

(2) A second Oligocene rhinoceros branch whose career, like that of the swimming rhinoceros, terminated before the close of that epoch, was the "running rhinoceros" (Hyracodon). This animal (Fig. 545) did not have the appearance which is usually associated with the rhinoceros, since it was light-limbed and agile, with horselike shoulders and limbs. It had three toes on each foot, very similar to those of the horse of its time, and was apparently adapted to the hard, dry plains of the Oligocene. It is possible that, had this animal succeeded in adapting itself to the changing conditions of the Tertiary and in competing with the other grazing

mammals of the time, it would eventually have dropped its side toes and have walked on one toe like the modern horse (p. 608).

(3) The true rhinoceroses constitute the third group, but with two exceptions (Diceratherium and Teleoceros), none of the North American forms had horns. None of this family are known to have lived in North America after the Pliocene, but members of the group were able to adapt themselves to the vicissitudes of the closing days of the Tertiary and roamed over Europe and Asia, some (woolly rhinoceros) being adapted even to the cold climate of northern Asia, as a carcass found frozen in the ice of northern Siberia shows.

The principal changes which the true rhinoceros group underwent in its history are (1) an increase in bulk, (2) a reduction in the toes from four on the fore foot to three on all the feet, (3) the development of horns, and (4) the development of somewhat better teeth.

REFERENCES FOR RHINOCEROSES

International Encyclopedia, — *Rhinoceros.*
Osborn, H. F., — *Age of Mammals*, p. 272.
Osborn, H. F., — *Phylogeny of the Rhinoceroses of Europe:* Bull. Am. Mus. Nat. Hist., Vol. 13, No. 5, 1900, pp. 229–267.
Scott, W. B., — *A History of Land Mammals in the Western Hemisphere*, pp. 326–353.
(A description of Arsinoitherium, an interesting Eocene animal with somewhat the appearance of a rhinoceros but unrelated, is to be found in Osborn, *Age of Mammals*, p. 202; and in Lankester, E. R., *Extinct Animals*, pp. 152–154.)

Tapirs. — It is interesting to find an animal living in the present which still retains the characters of animals that are more typical of Eocene and Miocene times before differentiation became marked.

The teeth of tapirs are short-crowned and differ but slightly from those of their Miocene ancestors of Nebraska and South Dakota. They are odd-toed ungulates (perissidactyls), with four toes (Fig. 541 *A*) on the fore foot (the weight being on the third toe), and three on the hind foot, the fourth toe of the fore foot being small. The Eocene ancestors of the tapirs graded almost insensibly into those of the horse and rhinoceros.

Tapirs live in marshes or dense forests in proximity to water, occupying a place in nature in which there is little mammalian competition. They had a wide distribution in the past and are an illustration of a once abundant race nearly exterminated but still struggling for existence where competition happens to be least severe in their particular case. Their present occurrence only in South

America and southern Asia seems remarkable unless one remembers that during the Tertiary tapirs ranged throughout the northern hemisphere, making their way to South America late in the Pliocene.[1]

Horses. — Few animals have a family history which goes so far back into the past and is at the same time so well-known as that of the horse. From an animal less than a foot in height, with a skeleton more like that of a carnivore than a horse, the changes in structure and size have been traced step by step to the present. It should be borne in mind, however, that few of the so-called ancestors are truly in the direct line, but they show us rather what the actual forebears were like.

Theoretically, the history of the horse begins with a generalized, five-toed animal which walked with the sole of the foot on the ground (plantigrade), or with the heel but slightly raised; with the normal number of teeth (44); with an arched back somewhat like a carnivore's, and with toes ending in nails which were neither hoofs nor claws; in other words, an animal similar to Phenacodus (p. 598).

FIG. 546. — Model of the Eocene horse *Eohippus*. (Restoration by C. R. Knight, under the direction of Prof. H. F. Osborn.)

The earliest American horse (Fig. 546) (Eohippus; Greek, *eos*, dawn, and *hippos*, horse) of which we have a record lived in the early Eocene and was a small and unhorselike animal about the size of a fox. It still retained the normal number of teeth (44), as did practically all of the animals of its time, the teeth being simple with very short crowns, somewhat resembling those of the pig and monkey, and very unlike the long, complicated grinders of the horse of to-day. So generalized are the teeth of this early horse that it is often a matter of great difficulty to distinguish them from those of the ancestors of what are now widely removed orders of animals. There were four well-developed toes

---

[1] If South America were raised in the central portion so as to permit the Amazon to deepen its valley and drain its basin, the tapir would doubtless become extinct in the New World. The lesson is an important one when the extinction of other animals is considered.

and a rudimentary first toe on the fore foot, while the hind foot had three toes and rudimentary first and fifth toes. The foot was a spreading one, enabling the animal to walk on fairly soft ground. From this earliest known, simple form, the course of evolution consisted largely in such modifications of the skeleton as rendered the animal better fitted to secure food and masticate it and to escape its enemies. This, as will be seen, resulted in the production of a very perfect grinding apparatus. The necessity for speed in seeking safety and in going long distances for food and water, resulted in the remarkably perfect locomotive apparatus.

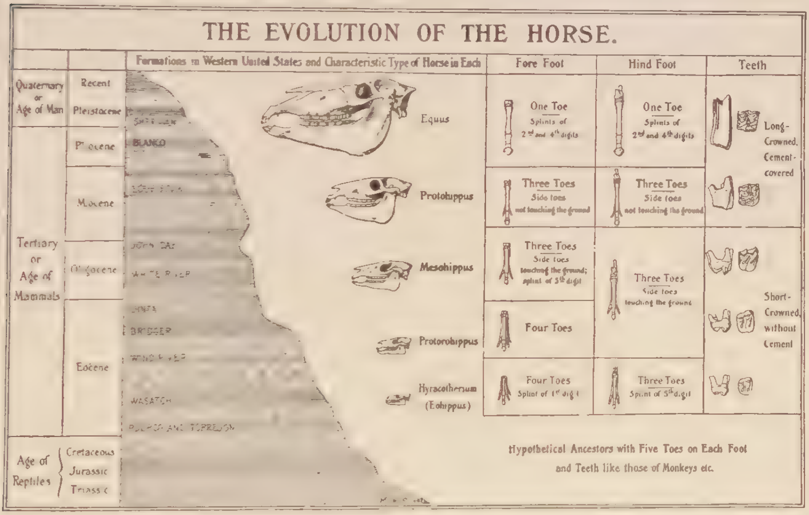


Fig. 547. — Table showing the evolution of the horse. (After W. D. Matthew.)

The next horse in the line of descent (Protorohippus, Fig. 547) appeared in the Upper Eocene and was four or five inches higher than the early Eocene horse (Eohippus), with longer limbs, which indicate ability for increased speed. The fore foot had four toes, but lacked the rudimentary toe, or splint, of the Eohippus, while a shortening of the outermost toe (the fifth) gave promise of a three-toed foot in its descendants. The hind foot had three toes but no splint.

The Oligocene horse (Mesohippus, Fig. 547) differs from the Eocene one (Protorohippus) in having but three toes on the fore foot and a splint which represents the outermost (or fifth) toe of the earlier horses. Besides the reduction in the number of toes, the leg had lengthened as the body thickened, and the animal stood about 18 inches high. The teeth were still short-crowned and lacked the complicated structure of the later forms.

A Miocene horse (Protohippus, or Hipparion, Fig. 547) shows the next stage in the evolution of the race. In these animals there was one large toe on each foot, with two smaller slender toes, one on each side of it, which were of no use to the animal, as they did not reach the ground when it walked. The teeth are very like those of the modern horse, in which the plates of enamel form curved, complex, irregular patterns (p. 602), but are shorter and probably wore out at an earlier age. The average height of the animal was about three feet. Associated with this more highly specialized horse (Protohippus) were others with short-crowned teeth and with all three toes functional (Parahippus and Hypohippus).

The stage between the Miocene horse (Protohippus) and the true horse (Equus, Fig. 547) is not definitely known, but was doubtless represented by an animal with a large central toe and with either very diminutive side toes or large splints, and longer and more perfect grinding teeth.

Summary of the Evolution of the Horse. — The changes, therefore, which took place in the horse family during its geological history are: (1) a reduction in the number of teeth from 44 to 36, accompanied by a lengthening and perfecting of the grinding teeth; (2) a reduction in the number of the toes from five to one; (3) an improvement of the joints of the legs by means of which motion was permitted in but two directions, forward and backward; (4) a lengthening of the limbs, especially in the lower portions. This has left the center of gravity high, and the limb, though long, moves quickly like a short pendulum, combining rapidity of movement with a lengthened stride; (5) an increase in the size of the animal; (6) a proportionally greater increase in the size of the brain than the body; (7) besides the above, other changes, such as the lengthening of the neck and head to permit the animal of increased height to crop grass from the ground; (8) the gradual perfection of the body; and others of which space will not permit mention.

Probable Cause of the Evolution of the Horse. — These radical structural changes seem to be the indirect result of a modification of the climate of the Great Plains region of North America and the accompanying change in the character of the vegetation. Eohippus was apparently an immigrant from Europe by way of Asia, but it was in America that the race developed, although from time to time modified representatives migrated back to Europe. During the Eocene the climate was moist, forests covered the lands, and lakes, marshes, and streams were abundant. Under conditions such as these the early horses lived. During the Oligocene the conditions had not greatly changed, but increasing aridity caused a drying up of the streams and lakes and the development of considerable areas of prairie lands. The woodlands, meadows, and dry prairies of the time favored the evolution of several branches adapted to the different environments, and the horse remains of the epoch show that branches, fitted for the varied conditions, were developed. Some of these soon became extinct, while others gave rise to the horses of the Miocene.

The great expansion of the prairies and diminution of the forested areas in the Miocene favored the evolution of horses fitted for rapid motion on the dry, hard plains. Two explanations for the increasing length and complexity of the teeth have been offered: (1) that, as the race changed from a habitat of forest and marsh to one of prairie, the teeth became fitted to grind up the hard, nutritious grasses that covered the plains (Osborn); and (2) that on dry, sandy plains where the grass was short, the teeth wore out rapidly because of the sand grains which were necessarily caught up with the grass when it was cropped, and which wore away the teeth even more rapidly than hard vegetation would. (Gidley.) Those who hold the latter view maintain also that the plains grasses were and are actually less hard than the vegetation of the marshes and forests, and that consequently a change to plains vegetation would have been unimportant had it not been for the presence of sand grains in the food. As a result of the above causes, we find the Miocene horses fitted for plains conditions increasing, and those with the spreading foot and short-crowned teeth fitted for forest conditions becoming extinct. After the Miocene the race became more and more like the modern horse. By the beginning of the Glacial Period they had become extraordinarily abundant, but at its close they had entirely disappeared from the western hemisphere, though the descendants of migrants to the Old World lived on.

Cause of the Extinction of the Horse in North America. — It is difficult to assign a reason for the extinction of the horses in America. The cold of the Glacial Period has been suggested, but is hardly adequate since the climate of the continent south of the ice sheets was not unfavorable, and at the present time horses on the western plains survive a temperature of many degrees below zero, without shelter or any food other than that which they can obtain for themselves, being able, in fact, to withstand conditions fatal to cattle and sheep. The suggestion that the extinction was due to some epidemic receives some support from the discovery of two species of tsetse fly in the Miocene deposits of Colorado, similar to the African types which, in that country, render thousands of square miles uninhabitable by horses. Epidemics such as that carried by the tsetse fly, the tick, and other insects are most prevalent in wet seasons. The moist conditions which are believed to have prevailed in North America during glacial times would favor the spread of such a disease over, perhaps, the whole of the New World and might readily wipe out of existence the entire race of horses.

REFERENCES FOR HORSES

Beddard, F. E., — *Mammalia.*
Flower, Sir W. H., — *The Horse.*
International Encyclopedia, — *Horse.*
Lankester, E. R., — *Extinct Animals*, pp. 132–142.
Lucas, F. A., — *Animals of the Past*, pp. 159–175.
Lull, R. S., — *The Evolution of the Horse:* Am. Jour. Sci., Vol. 23, 1907, pp. 161–182.
Matthew, W. D., — *The Evolution of the Horse:* Am. Museum Jour., Vol. 3, No. 1, 1903.
Osborn, H. F., — *The Evolution of the Horse in America:* Century Mag., Vol. 69, 1905, pp. 3–17.
Scott, W. B., — *A History of Land Mammals in the Western Hemisphere*, pp. 291–308.

Elephants. — The massive body and legs, the long tusks, and flexible trunk of the elephant combine to make it one of the strangest of animals and, from external appearance alone, one which might seem least likely to be descended from the generalized mammals of the early Eocene.

The earliest known fossil elephants (Mœritherium) (Fig. 548) have been found in Upper Eocene deposits of Egypt. They were about three and one half feet high and, even at this time, were of stocky build, although they would hardly be recognized as belonging to the elephant family were it not for later forms which became more and more elephantlike. The structure of the skull shows that a flexible upper lip, the beginning of a trunk, was present in life. The teeth had already been reduced to 36, and one pair of front teeth (incisors) in each jaw was longer than the others, giving promise of the great tusks of the elephant and mastodon. Those of the upper jaw were sharp-pointed and curved downward, while those of the lower jaw were directed upward. The grinders (molars) were somewhat ridged. The neck was of sufficient length to permit the animal to reach the ground in feeding.

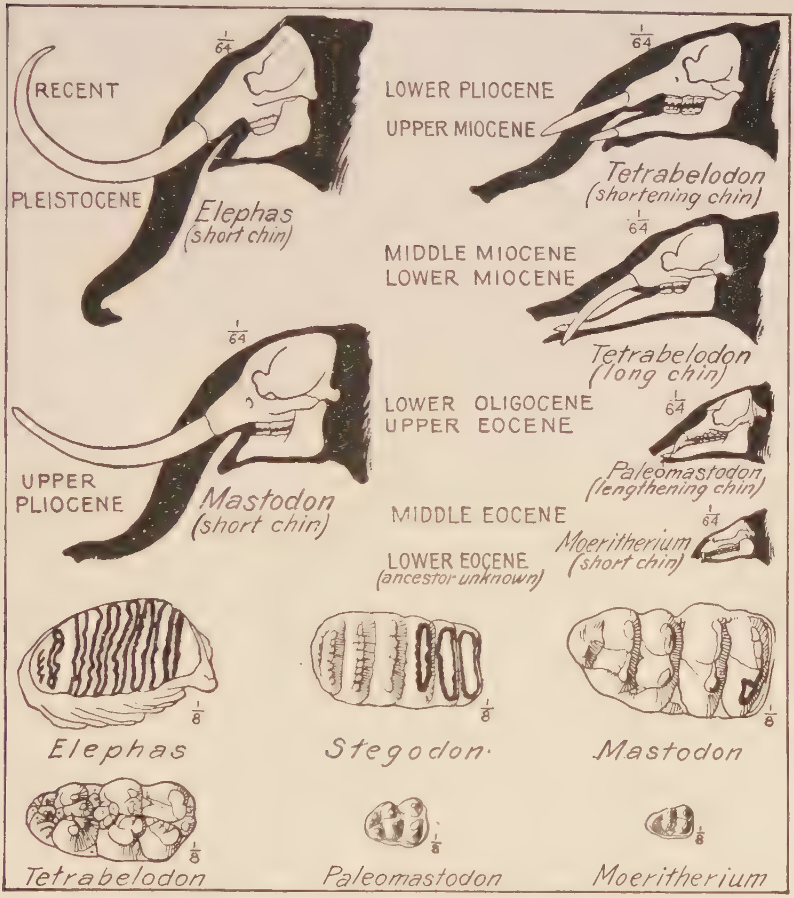


FIG. 548. — Chart showing the evolution of the elephant's head and teeth. (Modified after Lull and Scott.)

The next elephant in the line of descent (Paleomastodon) (Fig. 548) appeared in the Upper Eocene and was larger and stockier, with legs similar to those of its modern relatives. The upper and lower tusks were much longer than in the earlier form, those of the upper jaw being large, with a slight downward curve. This enlargement of the tusks was accompanied by a decrease in the total number of teeth, and the three-ridged grinding (molar) teeth were better instruments for mastication than those of the earlier elephant. The structure of the skull shows that the upper lip, in this form, had probably been developed into a short trunk which, however, may not have extended much beyond the lower tusks.

An elephant from the Miocene of France (Tetrabelodon), smaller than the modern Indian elephant, shows a great advance over those of the Eocene. This is to be expected, since no Oligocene elephants have yet been found. In this form the upper tusks are long and almost straight, while the lower are short, but since they are set in a greatly elongated lower jaw, they project almost as far as the upper. The trunk was longer than in the earlier members of the family, resting upon the lower jaw, and could only be raised and moved from side to side. As the trunk lengthened the neck shortened, since the animal could feed without the mouth's reaching the ground. Moreover, as the tusks and trunk became heavier, a long neck would have been a mechanical disadvantage. The teeth in this form are quite large and have numerous elevations and ridges. This genus spread over the Old World and North America, and by the dropping of the lower tusks which permitted the trunk to hang straight down, gave rise to the mastodon (Dibelodon). The mastodon differs from the true elephant in two principal particulars: (1) in the teeth (Fig. 548), which are composed of ridges covered with enamel, while the grinding surface of the elephant's tooth is made up of vertical plates of enamel and dentine, alternating with cement, the mastodon tooth being adapted for crushing succulent vegetation such as leaves and tender twigs, but not for grinding hard grasses, as is the elephant's; and (2) in the greater length of the lower jaw which in true elephants is remarkably short. The true elephants were apparently derived from a branch (Stegodon) that lived in India during the Pliocene. In this form the teeth show the first signs of developing cement between the ridges, which, by further development, formed the remarkable grinding apparatus of the mammoth and modern elephant.

Both the mastodons and the true elephants (mammoths) spread over North America, living here even after the disappearance of the last ice sheet, as is proved by the presence of skeletons in the bogs that have accumulated in the depressions of the latest glacial deposits. Paintings and carvings on ivory of mammoths, made by prehistoric man in Europe, prove the existence of elephants after the appearance of man on that continent. There is, however, no evidence pointing to their presence in North America since the advent of man.

FIG. 549. — Restoration of a Miocene elephant (*Dinotherium*) with tusks on the lower jaw. (After H. F. Osborn.)

Summary of the Evolution of the Elephant. — (1) The few (three in each half jaw) long, large, many-ridged teeth of the elephant, of which not more than one and one half are in use in each half jaw at one time, were developed from small, short-crowned, simple teeth with two poorly developed ridges. (2) The tusks are greatly elongated front teeth (incisors). (3) The trunk began as a short, flexible lip which, as the lower tusks became longer, gradually lengthened to enable the animal to reach the ground for food (Fig. 549). The trunk at first rested upon the lower tusks, but when these disappeared in the course of the evolution of the race, it hung straight down and because of this new position soon developed its present characteristics. (4) Accompanying the development of the trunk and tusks was a shortening of the neck. (5) The bulk and height of the animal increased and the leg straightened to support the greater weight.

REFERENCES FOR ELEPHANTS

OSBORN, H. F., — *The Elephants and Mastodons arrive in America:* Natural History, Vol. XXV, 1925, pp. 3–23.

LULL, R. S., — *Organic Evolution.*

SCOTT, W. B., — *A History of Land Mammals in the Western Hemisphere*, pp. 129–199; 422–442.

EVEN-TOED HOOFED MAMMALS (ARTIODACTYLS)

This division of the hoofed mammals (Fig. 540, p. 599) is the most important at present, being represented by such animals as the camel, deer, sheep, goat, and antelope.

Camels. — Evidence that the climate over large areas of the western interior of North America was dry for long periods of time is shown, as has been indicated (p. 611), in the evolution of certain animals — an evolution especially fitting them for life on the plains and deserts. The camel, as is well known, is admirably adapted for arid conditions. Its two-toed foot encased in a single pad is efficient in traveling over desert sand, its long, well-nigh structurally perfect legs enabling it to move rapidly and with the minimum effort, and its capacity for carrying water, were the results of a long evolution under such conditions.

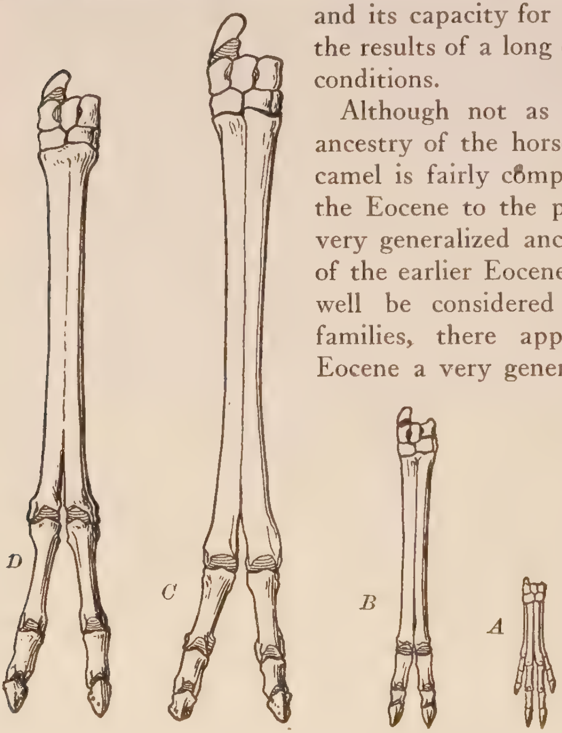


Fig. 550. — Evolution of the camel's foot from the Eocene to the present. (After Scott.)

Although not as well known as the ancestry of the horse, the history of the camel is fairly complete (Fig. 550) from the Eocene to the present. Following a very generalized ancestor (Trigonolestes) of the earlier Eocene, which may equally well be considered ancestral to other families, there appeared in the later Eocene a very generalized camel (Protylopus), a little larger than a jack rabbit, which is possibly ancestral to the modern camels. The points in which it differs most noticeably from living members of the family are: (1) the size; (2) the small, simple teeth of the normal number (44); (3) the presence of two side toes on each foot in addition to the two useful toes; and (4) the separate bones of the forearm (radius and ulna), which did not grow together until late in the life of the individual.

The Oligocene camel (Pöebrotherium) was of slender proportions, somewhat resembling a llama, though with a shorter neck. In this camel evolution had progressed in two principal particulars: the side toes were absent and were represented by splints, and the bones of the forearm were joined when the animal was still very young.

The next in line (Procamelus) lived in the Miocene and shows a further approach to the modern camel, having a longer neck than the preceding and more camel-like contour. In this stage the bones of the forearm were united before birth, and certain bones of the foot (metapodials, or "cannon bones") were united early in life. The splints were entirely absent. The animal was intermediate in size between the llama and camel. Some of the Pliocene and Pleistocene camels attained a larger size than any existing species. Besides these in the direct line of descent, a number of side branches arose to take advantage of various conditions of climate and food.

The camel is, in the even-toed line (artiodactyl), what the horse is in the odd-toed line (perissidactyl), each family having apparently progressed almost as far as possible in the perfection of its foot structure.

The camel family lived in the New World for perhaps 3,000,000 years and then completely disappeared from the North American continent, where its evolution had taken place. The camels (llamas and alpacas) of South America succeeded in living on in that continent, to which their ancestors had migrated in the Pliocene or Pleistocene. The entire family was confined to North America until the Pliocene, when it invaded the Old World, and in the Pliocene or Pleistocene it invaded South America. The dromedary and camel still survive in Africa and Asia, and the llama and vicuna in South America. Here again is a great family which, having developed into almost its present form in North America, became extinct on this continent, although still living on in others. The cause of the extinction of this family is as difficult to find as that of the horse; for, as in the case of the horse, the conditions in portions of America to-day (Arizona, New Mexico, and Mexico) have been shown by experiment to be as favorable for camels as those in their African and Asiatic homes, and they would doubtless be used in arid and semi-arid regions of western North America if economic necessity demanded. Their extinction in North America may have been due to the same cause, or causes, that produced the extinction of so many species at the close of the Pliocene.

REFERENCES FOR CAMELS

International Encyclopedia, — *Camel.*
Lull, R. S., — *Organic Evolution.*
Scott, W. B., — *A History of Land Mammals in the Western Hemisphere*, pp. 386–402.

Deer. — There are few, if any, cases in which the changes that the individual undergoes in his growth from birth to old age, so conspicuously parallel those which his ancestors underwent in the course of their geological history as in the deer. In the development of the existing deer the males and females are born hornless; at the end of the first year the male acquires a simple, one-pronged antler; this is shed, and at the end of the second year a two-pronged antler is grown; in the next year the antlers have two or three tines, and so on until the maximum number for the species has been reached. The geological history of the deer agrees in many particulars with the facts of individual development from year to year. The oldest known members of the tribe (Leptomeryx) (Fig. 551) in the Oligocene have no horns, as is true of their surviving relatives in Asia. The earliest deer with horns (Dicroceras) (Fig. 552 *A*) of which there is any record lived in the Miocene where the antlers were two-pronged. In the Upper Miocene deer with three-pronged antlers (Fig. 552 *B*) begin, and in the Pliocene the four-pronged (Fig. 552 *C*); then the five-pronged; and finally, near the close of the Pliocene, a deer appears in which the antlers are extremely branched. The deer first migrated into America after the two-pronged stage had been developed.

Fig. 551. — Hornless ancestral deer (Lower Oligocene). (After H. F. Osborn.)

Fig. 552. — Horns of deer, showing the evolution of horns. *A*, two-pronged deer of the Middle Miocene (*Dicroceras*); *B*, the three-pronged horn of the Lower Pliocene deer; *C*, the four-pronged horn of the Upper Pliocene. (Modified after Dawkins.)

The teeth of the Oligocene deer are very short-crowned, but in the course of the Tertiary they become longer and more thoroughly adapted to the mastication of plains vegetation. Various side branches appeared and became extinct during the period. Among them one unusual form (Protoceras) which was about the height of a sheep had two pairs of short, bony horns and canine tusks (Fig. 553). Its ancestry is unknown, and it probably reached North America by immigration.

FIG. 553. — A four-horned deer (*Syndyoceras*) (Upper Oligocene). (After H. F. Osborn.)

REFERENCES FOR DEER

MATTHEW, W. D., — *Osteology of Blastomeryx and Phylogeny of the American Cervidæ:* Bull. Am. Mus. Nat. Hist., Vol. 24, 1908, pp. 535–562.
ROMANES, G. J., — *Darwin and after Darwin*, Vol. 1, pp. 166–169.
WOODWARD, A. S., — *Vertebrate Paleontology*, pp. 363–365.

Cattle, Sheep, and Goats. — True cattle first appear, as far as known, in the early Pliocene deposits of Asia. Concerning the geological history of cattle, sheep, and goats little is known, since the difference in the ox, antelope, sheep, and goats is largely a matter of the curve of the horn and the build. This entire family (Bovidæ) have their maximum development at the present time.

Swine and Related Animals. — True pigs were confined to the Old World until brought to the New by Europeans, although their relatives, the peccaries, were abundant in portions of both North and South America. The entire family is very simple in structure, being the least altered of the descendants of the early, even-toed mammals (artiodactyls), and dates back to the early Eocene, although the oldest species of the true pig is not known before the Miocene. Several extinct families, distantly related to the pig, played an important part in the life of the Tertiary; and of these one (Entelodon) is especially worthy of mention. One species was as large as a rhinoceros, with a head four feet long. One peculiarity of the skull consisted in a prolongation of the cheek bones on either side of the lower jaw. They had two-toed feet, being rather highly specialized in this and other particulars.

Another generalized animal (Oreodon), in some respects combining the characters of the deer and hog but not ancestral to them, was extremely abundant at certain times during the Oligocene and Miocene and may have been partially responsible for the extinction of the titanotheres. It was not larger than a sheep, with a long tail and four-toed feet.

A Climbing Ungulate. — An interesting example of a modification in structure, fitting an animal for conditions very different from those to which its relatives were accustomed, is seen in a hoofed mammal, a member of the oreodont family (Agriochærus). In this Oligocene creature the feet and limbs are modified in such a way as apparently to enable it to climb trees as easily as a jaguar or other large cat. The hoofs are so narrow as to be actually converted into a sort of claw, and the wrist and ankle joints are modified in such a way as to make the wrists and ankles as flexible as those of a cat.[1]

Insectivores. — This primitive group occupied an important place in the Eocene, since which time it has dwindled in numbers and is now represented by a few survivors inhabiting, for the most part, uncongenial regions, or else protected by spiny armor, or of subterranean habits. It is represented by the mole, hedgehog (not the porcupine), shrew, and other small animals that feed largely on insects and worms. Insectivores have remained simple in their organization since their introduction and are the least altered of the great branches. Among their generalized characters are the smooth brain, five-clawed toes, the habit of walking with the whole or greater part of the soles to the ground (plantigrade), and other less conspicuous features. The group is so generalized, in fact, that it is difficult to characterize it without a too technical description. Perhaps the most striking feature of some living genera is the elongated, or proboscis-like, nose. It is possible that this group more nearly represents the characters and habits of the primitive true mammals (Eutheria) than any other now living. There seems to be little doubt that bats are descendants of primitive members of this group.

Rodents (Gnawing Animals). — Rodents are first known from the Eocene, before the close of which epoch they had acquired practically all their present characteristics. With the exception of their powerful gnawing teeth (incisors), rodents, in the past and present, have been animals of simple structure. Their brains are smooth, and the race has apparently changed in no essential feature since Eocene times, with the exception of their teeth which have been slightly reduced in number, and the grinders (molars and premolars), in some species, have become perhaps as highly developed as those of any other class. Before the close of the Oligocene, squirrels, marmots, beavers, rabbits, pocket gophers, and others were present.

A burrowing rodent with horns, which appears in the Miocene and early Pliocene, is interesting as showing the possibility of variation. It seems to have been much better adapted for digging than existing gophers, but of what use the horns could have been

---

[1] Matthew, W. D., — *A Tree-Climbing Ruminant:* Am. Museum Jour., Vol. 11, 1911, pp. 162–163.

to a burrowing animal it is difficult to imagine. They may have served as accessories to the strong claws in digging, or they may prove to be sexual characters.

In the Eocene there also appeared a race (Tillotherium) (Figs. 554 *A*, *B*) similar in habits to the rodents, although not of this tribe, some members of which grew to be of considerable size, one species being half as large as the tapir. In South America during the Miocene rodents were abundant, but all belonged to the great porcupine group such as live on that continent to-day; the forms common in North America at that time, the rats, mice, squirrels, beavers, marmots, hares, and rabbits, being absent.

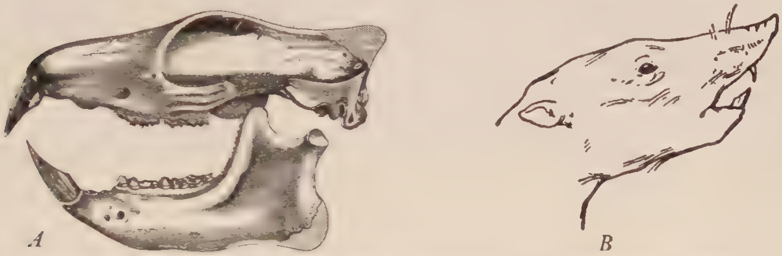


Fig. 554. — *A*, skull; and *B*, restoration of the head of *Tillotherium*, a peculiar rodent-like creature (Eocene). (After H. F. Osborn.)

It is an interesting fact that, notwithstanding their failure to develop a highly complex brain, rodents are, at present, the most abundant of mammals. This has been possible because of their fecundity and adaptability to varying conditions.

REFERENCES FOR RODENTS

Gidley, J. W., — *A New Horned Rodent from the Miocene of Kansas:* Proc. U. S. Nat. Mus., Vol. 32, No. 1554, 1913.
Woodward, A. S., — *Vertebrate Paleontology*, pp. 373–374.

Edentates (Latin, *edentatus*, toothless). — The earliest Eocene edentates (Ganodonta) were so similar to the ancestral herbivores (Condylarthra) and carnivores (Creodonta) that it seems probable that the three orders were derived from a common ancestor only a short time before. The most familiar living edentates are the armadillos, the anteaters, and the sloths. The name, edentate, is misleading, since most of the order have teeth which are much alike and are without enamel. Teeth, however, are lacking in the front part of the mouth, and it was from this character that the name was given. One modification — among a number — should be mentioned. In the earliest forms the teeth were covered with enamel, as is commonly true of mammalian teeth, and had definite roots. In the later forms the teeth become rootless, and the enamel disappears except in narrow bands. It is rather surprising to find armadillos (Metacheiromys) as far back as the Eocene, similar in many respects to the smaller armadillos of to-day, but apparently possessing a leathery instead of a bony shield and with different teeth.

The order did not attain great importance until the Pliocene and Pleistocene, at which time (p. 670) it assumed a leading rôle in South America. Some of the South American edentates were the largest creatures on that continent. The description of the South American sloths will be taken up in the discussion of Pleistocene mammals.

True Carnivores. — When traced back, it is found that such distinct families as the dog, hyena, and cat become less and less easily distinguished, until they converge in the primitive carnivores (Creodonta, p. 594) of the Eocene; and these, in turn, have affinities with both insectivores and ancestral hoofed mammals (Condylarthra). Before the close of the Oligocene many families of the true carnivores appeared and lived in competition with the ancestral carnivores, which they entirely replaced before the close of the Oligocene.

In the Eocene and Oligocene primitive representatives of the families to which belong the dog, weasel, cat, and hyena appeared; but the families were more clearly differentiated in the latter, at which time ancestral dogs, raccoons, and weasels were common although not yet of a distinctly modern type. In the epoch following (Miocene) carnivores were abundant, and some of them so closely resemble those of to-day that they have been included in the same genera as living animals. Wolves, foxes, panther-like animals, saber-toothed tigers, ancestral raccoons, as well as weasels and other like forms were present. In Europe the bear and hyena were represented as well as the above. In the Pliocene carnivores flourished and perhaps gained on the herbivores, forcing them to develop greater speed, sagacity, and powers of defense.

In South America during the Miocene there were no true carnivores; but their place in nature was taken by carnivorous marsupials, such as live in Australia to-day.

Primates (Monkeys, Apes, Lemurs). — This order of mammals has especial interest because it also includes man. The first known members (lemurs) date back to the earliest Eocene deposits, where their remains so closely resemble those of the generalized insectivores of that early time that it is difficult to distinguish one from the other. Monkeys and lemurs lived in North America during the Eocene, but disappeared from this continent at the beginning of the Miocene. Primate remains from the Miocene of France (Dryopithecus) are of great interest because of the similarity in some respects to the skeleton of man, and also because of the possibility that these animals were able to make rough flint implements (eoliths, p. 675). " How far it may be regarded as a stem from which on the one side the line led to the human race and from the other to the living anthropoids, namely the chimpanzee, orang, gibbon, and gorilla cannot be certainly determined." (Osborn.) The discussion of the so-called man-ape (Pithecanthropus) and others will be taken up in connection with the evolution of man in the next epoch.

REFERENCES FOR PRIMATES

BEDDARD, F. E., — *Mammalia.*
WOODWARD, A. S., — *Vertebrate Paleontology,* pp. 403–410.

Birds. — The presence of birds in the Lower Eocene, typically modern in structure and in no sense intermediate between the Mesozoic toothed birds with vertebrated tails and the birds of to-day, makes the question as to the origin of the typical Tertiary life (birds and mammals) exceptionally difficult in the present state of our knowledge. (The discussion under Rise of Mammals, p. 590, should be considered in this connection.)

Although few of the birds of the Eocene can be referred to living genera, they are modern in all essential features. Even at this early date there were living relatives of the vultures, storks, secretary birds, sandpipers, Old World quail, sand grouse, cuckoos, swifts, herons, and pelicans. The appearance of a great, flightless bird (Gastornis) as large as an ostrich but apparently unrelated, presenting affinities to wading and aquatic birds, is interesting as showing the advanced stage of evolution at this early time.

The bird life of the Eocene of Europe (Quercy, France) gives a clue to the climate and environment of portions, at least, of Europe at that time, since it was fitted to inhabit great, warm plains, scattered over with groves. The assemblage is a tropical one and approaches that now found in tropical Africa and South America, although, as in the case of the vegetation (p. 634), tropical forms are associated with others that are now typical of temperate regions.

Most of the bird fossils are from the Miocene and later formations, and belong to existing families and often to existing genera. A remarkable bird (Phororhachos) from the Miocene deposits of Patagonia shows the extreme to which bird evolution may be carried. It stood about seven feet high and had a head as long as that of a horse, armed with a pick-like projection. Its habits have been variously conjectured. The loss of wings indicates a semiarid condition.

In general, it can be said that the earliest Tertiary birds are typical modern birds, modified for various conditions of life, some being aquatic, some waders, and some land birds; and that the changes which took place during the period resulted in the production of modern genera and species. Although 12,000 species of birds are living to-day, less than 500 are known from the Tertiary. The reason for the rareness of bird remains, as has already been discussed (p. 563), is probably due to their lightness, which causes them to float and thus exposes their carcasses, often for many days, to fish and other carnivorous animals.

REFERENCES FOR BIRDS

Hutchinson, H. N., — *Extinct Monsters and Creatures of Other Days*, pp. 220–224.
Lucas, F. A., — *Animals of the Past*, pp. 138–158.
Osborn, H. F., — *Age of Mammals*, pp. 151, 152, 195, 257, 450.
Woodward, A. S., — *Vertebrate Paleontology*, p. 244.
Zittel–Eastman, — *Textbook of Paleontology*, Vol. 2, pp. 268–278.

Reptiles and Amphibians. — The usual practice at present is to include in the North American Tertiary no formations containing dinosaur remains. This is the custom even though a great unconformity exists in the Laramie (p. 517) of the western interior of North America, which, were it not for the presence of dinosaur fossils in the formation (Lance) overlying the unconformity, would doubtless be considered the dividing line between the Mesozoic and Tertiary. The most conspicuous reptilian survivors of the Mesozoic were the turtles, crocodiles, and large river lizards (Champsosaurus), the last, however, disappearing early in the period. Snakes began in the Cretaceous, having doubtless been derived in the Mesozoic from lizards, by the degeneration of their limbs. A number of species have been found in the Tertiary, few of which, however, are to be distinguished from those now living, and the majority belong to the non-poisonous varieties. Some of the early sea snakes attained a length of about 20 feet.

Among amphibians, salamanders, newts, frogs, and toads occur in Oligocene deposits; and numerous impressions of tadpoles have been preserved.

Deductions as to the climate of the Tertiary can be made from the reptilian life as well as from the vegetation (p. 634). Crocodiles, large and small, and of several genera, lived in abundance in the Middle Eocene (Bridger) of the western interior and suggest a climate not unlike that of Florida to-day, and a country similar to the bayou region of the Mississippi delta. The rivers of this time swarmed with turtles, but the presence of land tortoises, some of which were three feet long, indicates that these swampy areas were bordered by extensive stretches of dry land. Numerous land tortoises in the Oligocene deposits of the Great Plains show that dry-land conditions were widespread. Since spiny lizards are largely confined to-day to arid regions, the presence of numerous lizards (Glyptosaurus) with skulls covered with spiny, bony plates is indicative of dry conditions in Montana during a portion, at least, of the Oligocene.

REFERENCES FOR REPTILES AND AMPHIBIANS

Cunningham, J. T., — *Reptiles, Amphibians, and Fishes.*
Osborn, H. F., — *Age of Mammals*, pp. 208–209.

Fishes. — The fish of the Tertiary were abundant and very similar to those of the present seas. Ganoids were represented by a few species, and teleosts were very much as at present, both in numbers and in appearance. The most noted deposit of fossil fish in America is that of the Green River (Eocene) shales of Wyoming, where thousands of beautifully preserved specimens have been quarried, examples of which can be seen in almost any museum. The great number of sharks' teeth (Fig. 555 *A–D*) in the Tertiary deposits of the Atlantic Coastal Plain of North America and elsewhere show that sharks were very abundant in this period. Some of them must have been of great size, judging from the teeth some of which are six and one half inches long and six inches broad. A close living relative, the great white shark, has teeth one and one fourth inches long. If

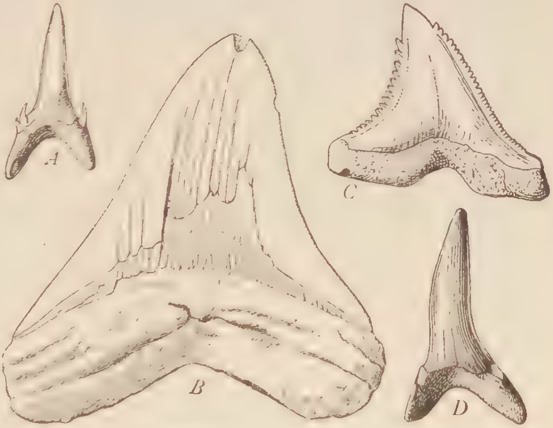


Fig. 555. Tertiary shark teeth: *A, Odontaspis cuspidata; B, Carcharodon megalodon; C, Hemipristis serra; D, Odontaspis elegans.* (After Maryland Geol. Surv.)

the proportion of size of teeth to length of body holds true in the two species, the giant Tertiary shark (*Carcharodon megalodon*) attained a length of 70 to 80 feet and possessed jaws five to six feet across. No actual measurements of these sharks have been made, since their skeletons, being cartilaginous, have not been preserved.

REFERENCES FOR FISHES

DEAN, B., — *Fishes Living and Fossil.*
OSBORN, H. F., — *Age of Mammals*, pp. 136, 160, 216, 339–340.

INVERTEBRATES

During the Tertiary, limestone strata several thousands of feet thick were built up by the accumulation of the remains of invertebrates. This is in marked contrast to the deposits formed of vertebrate remains, which are never of great thickness, and seldom form even thin beds of great extent. Limestone, locally of enormous thickness and extent, covering areas in the Pyrenees and the Alps mountains, in Greece, northern Africa, Persia, China, and Japan, is often made up chiefly of the shells of Foraminifera named Nummulites (Latin, *nummus*, a coin) (Fig. 556) from the shape and size (p. 577). Perhaps at no time in the entire history of the world did an organism of similar size live in greater abundance. Other limestones in Europe and on the Gulf Coast of North America were formed in large part of other forms of Foraminifera.

FIG. 556.—Tertiary Foraminifera: *Nummulites*. An enlargement of a portion of the shell is seen in the upper left-hand corner.

Brachiopods and crinoids were rare throughout the period and may be considered as races about to become extinct. Sea urchins (Fig. 557) continued to be abundant.

Coral reefs are rare in the Eocene and had a distribution different from that of to-day, well-developed reefs occurring on the north and south flanks of the Alps and Pyrenees. In the Miocene and Pliocene they had almost their present distribution.

Gastropods and pelecypods (Figs. 558, 559) were abundant throughout the Tertiary, being, as now, the most numerous of the larger invertebrates. During the period they became more and more like the living forms, until in the Pliocene they were nearly identical with those of to-day. Certain species are characteristic of the various formations of the epoch and are consequently of great stratigraphic value. Some Miocene pelecypods attained a large size; oysters 13 inches long, 8 inches wide, and 6 inches thick, as well as pectens (Fig. 558 *I*) 9 inches in diameter are known. Large size was not, however, characteristic of the pelecypods of the period. Larger pelecypods are living to-day than in any previous period.

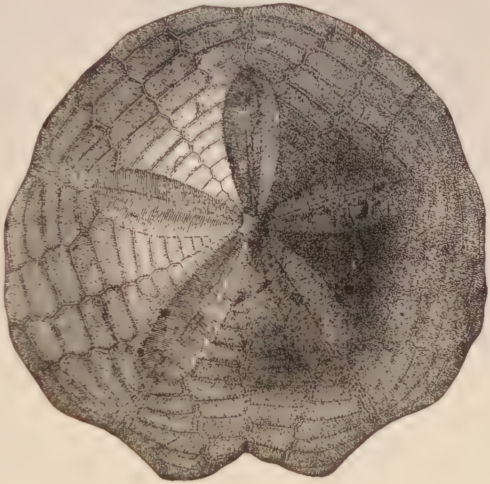


Fig. 557. — Tertiary echinoid: *Scutella aberti* (Miocene). (Maryland Geol. Surv.)

The cephalopods were represented by the nautilus and squid, the former having a wider distribution than now.

Insects. — At the present about 400,000 living species of insects have been described, but less than 8000 fossil species are known. The small number of fossil insects as compared with those of the present does not indicate that this class is more numerous to-day than at certain times in the Tertiary, but rather that few of the Tertiary species have been preserved. It has even been suggested that owing to the warmer climate and more luxuriant vegetation, and judging from the proportion of species, the total insect fauna of the Miocene of Europe may have been greater, in some respects, than it is now in any part of that continent. The greater number of Tertiary insects have been preserved in amber, in which they were entrapped when the gum of the trees on which they were crawling was first exuded and was soft and sticky. About 2000 species have been thus preserved, some of the specimens of which are in an almost perfect state of preservation, all of the external characters being as well shown as in life; others are preserved in peat; and still others in

FIG. 558. — Tertiary invertebrates: *A*, *Venericardia planticosta* (Eocene); *B*, *Ostrea sellæformis* (Eocene); *C*, *Turritella humerosa* (Eocene); *D*, *Hercoglossa tuomeyi* (Eocene); *E*, *Turritella mortoni* (Eocene); *F*, *Ecphora quadricostata* (Miocene); *G*, *Volutilithes petrosus* (Eocene); *H*, *Orthaulax gabbi* (Miocene); *I*, *Pecten madisonius* (Miocene); *J*, *Turritella variabilis* (Miocene).

mud. The finely laminated shales of Oeningen, on the Lake of Constance, Florissant, in Colorado, and elsewhere have yielded hundreds of specimens.

Horseflies, Tsetse Flies, and Ants. — The presence of horseflies very similar to living forms in the Miocene deposits (Florissant, Colorado) is interesting, as it shows that, even at that early date, the horse was probably tormented by this insect. Although the horse has changed radically, the flies have remained practically the same. In the same deposits (Florissant, Colorado) the tsetse flies occur. "The exquisitely preserved ants of the Baltic amber, belonging to the Lower Oligocene formation, are in all respects like existing ants. All of them belong to existing subfamilies, most of them even to existing genera, and a few of them are practically indis-

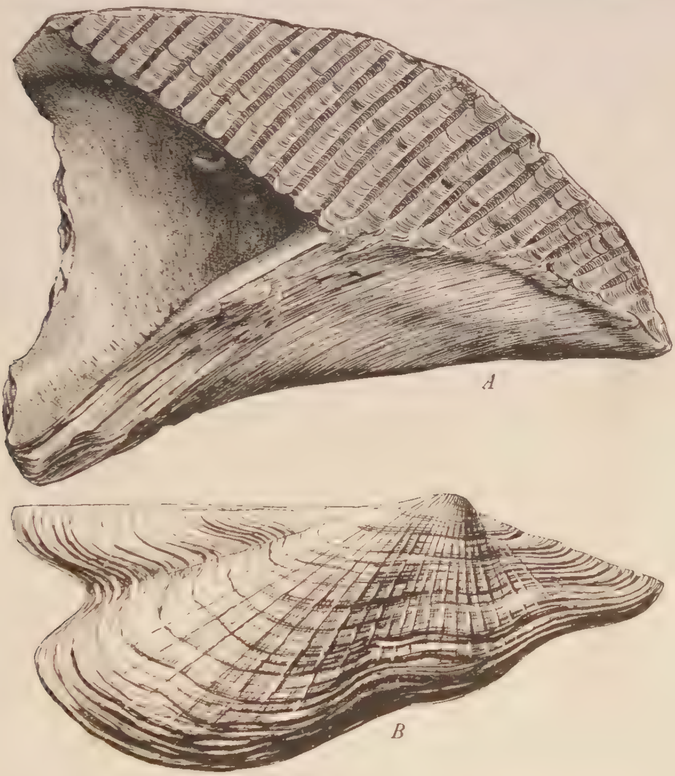


FIG. 559. — Tertiary pelecypods: *A*, *Melina* (*Perna*) *maxillata* (Miocene); *B*, *Arcoptera aviculæformis* (Pliocene). (Maryland Geol. Surv.)

tinguishable from species inhabiting Europe to-day. That some of them were herders of plant lice is proved by blocks of amber containing masses of ants mingled with the plant lice which they were attending when the liquid resin of the Oligocene pines flowed over and embedded them. Possibly the soldier cast is a recent innovation, but the differentiation of the males, queens, and workers was as extreme, and precisely of the same character as now." (W. M. Wheeler.)

The insects of these Colorado Miocene deposits indicate that the locality was doubtless an upland or mountain with a warm, moist, but not tropical climate. The presence of such a climate in the higher lands of this epoch does not preclude the possibility of arid conditions on the Great Plains and in Texas (p. 635).

There appears to have been but little important change in the insect world since the middle of the Eocene or earlier, almost no new orders or even families having appeared, although the genera and species have changed. This is perhaps not surprising, since insects of the modern type made their appearance soon after flowering plants became widespread, and had consequently perfected their structure and organs previous to the Tertiary, during the long Cretaceous Period.

REFERENCES FOR INSECTS

Osborn, H. F., — *Age of Mammals*, pp. 263, 450.
Zittel–Eastman, — *Textbook of Paleontology*, Vol. 1, pp. 794–821.

Vegetation

The vegetable kingdom reached its culmination before the animal kingdom; and as far as plant evolution is concerned, it is almost arbitrary to separate the Tertiary from the Mesozoic or from the Pleistocene. Even at the beginning of the Tertiary, the general aspect of the forests was not very different from that of to-day, as the presence of maples, poplars, sycamores, walnuts, hazelnuts, elms, yews, cedars, and sequoias (redwoods) shows. The association, however, is rather remarkable since with the above are found figs and palms. The presence in Greenland, Iceland, and Spitzbergen of trees such as now grow in the United States indicates a warmer climate in the polar regions.

Grasses. — There was, however, one very important element of the vegetation — the grasses — which at the beginning of the period apparently occupied a very subordinate position, but which before its close became widespread. Because of the part played by this type of vegetation in the evolution of the most important branch of mammals (ungulates, hoofed mammals) it will be well to discuss the evidence upon which its presence is based. "If we observe the conditions of the preservation of plant remains along existing ponds, river borders, or swamps, we see at once that they are as favorable for the preservation of deciduous leaves as they are unfavorable for the preservation of grasses. Grasses are firmly attached to their roots and are not swept away either by water or wind. Leaf deposits, therefore, abound everywhere and give us sure indications of the forest flora, while we know but little of the field and meadow flora, which is of great importance in connection with the evolution of the grazing herbivorous ungulates especially. In fact, the evidence as to grasses is very limited throughout the entire Age of Mammals. The number of kinds of grasses (Graminæ) found in the whole Cenozoic of Europe is comparatively small, and it is difficult to draw conclusions from fossil plant remains alone as to their relative or absolute importance. At what period grasses began to assume anything like their present dominance it is impossible to determine. The absence of native grasses in Australia is indirect evidence of their late geological development." (Osborn.) The indirect evidence of the history of grasses, derived from the adaptation of the teeth of the hoofed mammals, "disposes us to adopt the opinion that grasses attained wide distribution in both hemispheres only toward the close of the Eocene. Their evolution on favorable forestless regions was certainly a prolonged one, beginning in Mesozoic times." (Osborn.) Proof that grasses were widespread in the Miocene is based upon the structure of the mammals; omnivorous forms were becoming grass eaters; the method of chewing was changing from a vertical, biting movement to a horizontal, grinding one; and the teeth were becoming more durable and better suited for grinding hard food. This then was apparently the time at which the grassy plains began.

Dæmonhelix. — Certain fossils occurring abundantly in the Miocene deposits in a restricted area of western Nebraska have given rise to some speculation. They consist of spirals (Fig. 560) of harder rock, held together by fibrous calcareous material which sometimes shows a vegetable structure, and because of their shape and size they have received the name Dæmonhelix (Devil's Corkscrew). Some of them are ten feet or more in height and a foot in diameter;

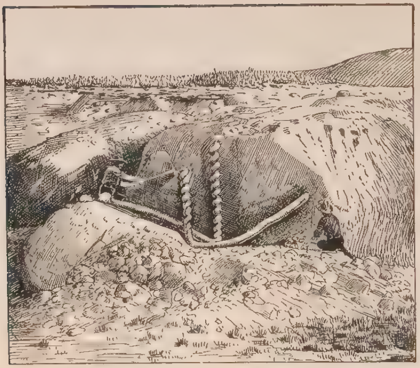


FIG. 560. — Dæmonhelix, Nebraska. (Redrawn after E. H. Barbour.)

and since they resist erosion somewhat better than the surrounding rock, they often stand out prominently against the bluffs. They have been considered the burrows of extinct rodents and also fossil algæ, but the proof of the latter seems now to be well established.

Geological History of Sequoias. — The history of the sequoias (big trees and redwoods) of California is a striking example of the fate of many animals and plants, and illustrates the difficulty of finding the cause of extinction in plants as well as animals. These big trees, which sometimes grow to a height of 325 feet, have a girth of 50 or 60 feet, and live to be 5000 years old, are now confined to the mountain slopes of California. In the Tertiary the sequoias were common trees in the northern hemisphere, extending from Spitzbergen (78° north latitude) as far south as the middle of Italy, in Asia to the Sea of Japan, and over a large part of North America. The sequoias date back to the Cretaceous, where they were undoubtedly represented by several species. "This is perhaps the most remarkable record in the whole history of vegetation. The sequoias are the giants of the conifers, the grandest representatives of the family, and the fact that, after spreading over the whole northern hemisphere and attaining to more than 20 specific forms, their decaying remnant should now be confined to one limited region in western America and to two species constitutes a sad memento of departed greatness. The small remnant of *Sequoia gigantea* (the big trees) still, however, towers above all competitors, as eminently the "big trees," but, had they and the allied species failed to escape the Tertiary continental submergences and the disasters of the Glacial Period, this grand genus would have been to us an extinct type." (Dawson.) It is stated that the sequoias were so abundant in northwest Canada as to furnish much of the material for the great lignite beds of that region. That the climate of other parts of the world is still suited to the growth of these trees is shown by the fact that sequoias are now growing in England and around Lake Geneva in Switzerland from seeds carried there from California. Their disappearance becomes more remarkable since it is known that "under the most favorable conditions these giants probably live 5000 years or more, though few of the larger trees are more than half as old." One careful observer says, "I never saw a big tree that had died a natural death: barring accidents they seem to be immortal, being exempt from all the diseases that afflict and kill other trees. Unless destroyed by man, they live on indefinitely until burned, smashed by lightning, or cast down by storms, or by the giving way of the ground on which they stand." (John Muir.)

Diatoms. — The earliest specimens known with certainty to be diatoms are from the Jurassic. This group did not become common until the Cretaceous, or abundant until the Tertiary. A stratum 50 feet thick in Bohemia is almost entirely composed of diatoms; about Richmond, Virginia, there is a deposit 30 feet thick and many miles in extent; and deposits of diatomaceous earth are common in other parts of the Coastal Plain. Thick beds also occur in the California Tertiary (p. 581). Diatom deposits are now forming in the Yellowstone National Park, where "they cover many square miles in the vicinity of active and extinct hot spring vents of the park, and are often 3 feet, 4 feet, and sometimes 5 to 6 feet thick." In the Tertiary, diatom deposits were formed in sluggish streams, in lakes, on the sea bottom, and in hot springs, as they are now in Nevada and California. The Cretaceous and Tertiary species very closely resemble living forms.

Exceptional Preservation of Plants. — The preservation of such delicate parts of plants as flowers, catkins of the oak, pollen grains, as well as fungi, in the amber of Oligocene trees, gives us almost as definite knowledge of some of the Oligocene plants as if they were living to-day.

In certain parts of Europe Oligocene mineral springs covered with their deposits whatever organic remains they touched and thus buried them. After a time the organic matter decayed, sometimes leaving perfect molds of their forms. When these molds are properly filled, casts even of fossil flowers and insects are sometimes obtained.

Plant Localities in North America. — About 500 species of Miocene plants are known in North America, but the deposits in which they are found are small and widely separated. One at Brandon, Vermont, consists of a small, pocket-like deposit of lignite, at one time worked for fuel, which has yielded a large number of fossil fruits, among which walnuts and hickory nuts have been identified, although most of them are of unknown or doubtful affinity. In Colorado (Florissant) the deposits of a Miocene lake (p. 580) have afforded large numbers of plants, such as alders, oaks, narrow-leafed cottonwoods, pines, roses, thistles, asters, and Virginia creepers. Mixed with these are others of a more southern type, such as the holly, smoke tree, sweet gum, and persimmon. The vegetation of the Pliocene was probably almost identical with that in the adjoining regions to-day, but so few plant fossils have been found that no definite statements can be made.

Climate

Difficulty in Determining Tertiary Climates. — The determination of the climates of the Tertiary is complicated by a mingling of plants whose *relatives* are no longer found associated, some being at present restricted to tropical or subtropical regions and others to temperate zones. Since closely related modern species sometimes live under very different climatic conditions, it will readily be seen that the presence of plants in the Tertiary related to species now living only in subtropical regions, for example, does not necessarily prove that these early species lived under similar conditions, but is certainly strong evidence in favor of such a supposition; especially when it can be shown that the plant associations were then the same as now; *e.g.*, breadfruit trees, cycads, and many ferns grew in association in Greenland (72° N.) as they now do in the tropics. This mingling of what are now tropical and temperate region types has led investigators to very different conclusions. For example, the Miocene climate of Colorado, because of the presence of genera now living in Colorado, is believed by one investigator (Cockerell) to have been in no sense tropical, while another (Knowlton), because of the presence of West Indian genera, believes that the climate was not unlike that of certain parts of the West Indies of to-day. Certain trees, such as palms, are generally agreed to indicate warm, tropical, or subtropical conditions, even when they grew in forests with the maple, elm, and other temperate region plants. When, however, the remains of insects, reptiles, or mammals occur in deposits with plants, the total evidence often becomes conclusive.

Eocene. — The vegetation suffered so little change between the Upper Cretaceous and the Eocene that it is evident the climates of the two epochs were not unlike. In the early Eocene (Fort Union), a cool to mild temperate climate, with a much greater rainfall than now, prevailed over the Dakotas, Wyoming, Montana, and as far north as the Mackenzie River in Canada, as is shown by the remains of the walnut, hickory, viburnum, grape, elm, poplar, sequoia, and yew, and by the presence of numerous, often thick, beds of lignite. In the earliest Eocene the vegetation of Greenland, Iceland, and Spitzbergen included alders, magnolias, lindens, poplars, and birches, indicating a climate similar to that of south temperate France and California at the present time. In the later Eocene palms flourished in southern England; and the waters were tenanted by crocodiles and giant sea snakes, indicating a climate like that of tropical America to-day, and warmer than in the western interior of North America.

Oligocene. — The climate of the Oligocene in Europe appears to have been slightly cooler than during the Eocene. The occurrence of palms in the Baltic region, however, indicates a temperature such as now prevails in Spain and Italy. Nothing is known of the grasses, and the development of the teeth of the mammals does not afford a positive proof of their presence. The presence of crocodiles in the Oligocene deposits of South Dakota implies a climate such as is now found in Florida.

Miocene. — Although the vegetation is similar to that of the Oligocene, there is evidence of a gradual lowering of the temperature in the Miocene; palms ceased to exist north of the Alps; and towards the end of the epoch there was a lowering of the temperature in the Arctics. In Colorado Miocene deposits no palms have been found, but the presence of figs, which now do not grow north of the coast of the southern states, and of two genera of trees which are now confined to the tropics (Weinmania) indicates that the climate of this mountainous region was more equable, moister, and somewhat warmer than now, although it is probable that on the Great Plains arid conditions prevailed. A layer of fan-palm leaves a foot in thickness in a formation of this epoch in northern Washington points to almost tropical conditions in that region. The occurrence of breadfruit trees associated with temperate region trees in the Middle Miocene of Oregon indicates a somewhat warmer climate there than now.

Pliocene. — The gradual cooling of the climate of Europe continued in the Pliocene, during which epoch there was a slow southward movement of the northern forest trees and a disappearance of delicate tropical types. Towards the very end of the Pliocene there was a marked lowering of the temperature and perhaps the beginning of glaciation on the higher mountains. In the English Pliocene the proportion of Arctic shells rises from five per cent. in the oldest to over sixty per cent. in the youngest beds.

The disappearance of rhinoceroses and the browsing types of horses and camels (those that lived largely on the leaves of shrubs and trees), as well as the existence of great herds of land tortoises on the Great Plains of North America, is perhaps proof of arid conditions in the western interior. The disappearance on the Pacific coast of warm temperate plants, as well as the character of the marine and fresh water invertebrates, indicates a change to colder conditions. Evidence is at hand showing that Japan was colder during the Pliocene than during the Glacial Period (Yokohama). This has again suggested the possibility of a "wandering pole" to account for the Glacial Period.

REFERENCES FOR FLORA AND CLIMATE

Knowlton, F. H., — *The Relation of Paleobotany to Geology:* Am. Naturalist, Vol. 46, 1912, pp. 207–215.

Knowlton, F. H., — *Succession and Range of Mesozoic and Tertiary Floras:* Jour. Geol., Vol. 18, 1910, pp. 105–116.

Osborn, H. F., — *Age of Mammals,* pp. 104; 117; 184–185; 242–244; 282–285; 306; 342–343.

Schuchert, Chas., — *Climates of Geologic Time:* Carnegie Institution of Washington, Publication No. 192, 1914, pp. 263–298.

Effects of Isolation and Migration

During the Age of Mammals the seas were at times so expanded as to isolate large areas of land, while at others they were so restricted that continents now separated were then united (Figs. 561, 562, 563). The mammalian life of Cuba seems to have been derived from a few species that were carried there on natural rafts. Other islands were doubtless populated in the same way. When the isolation was prolonged, the evolution of the animal life of the various continents took place independently. When the lands were again united, widespread migrations took place. This isolation and later establishment of land connections occurred several times during the Tertiary. The proof of the separation or reunion of great land areas is based chiefly upon the dissimilarity in the one case, and the similarity in the other, of the life of the past.

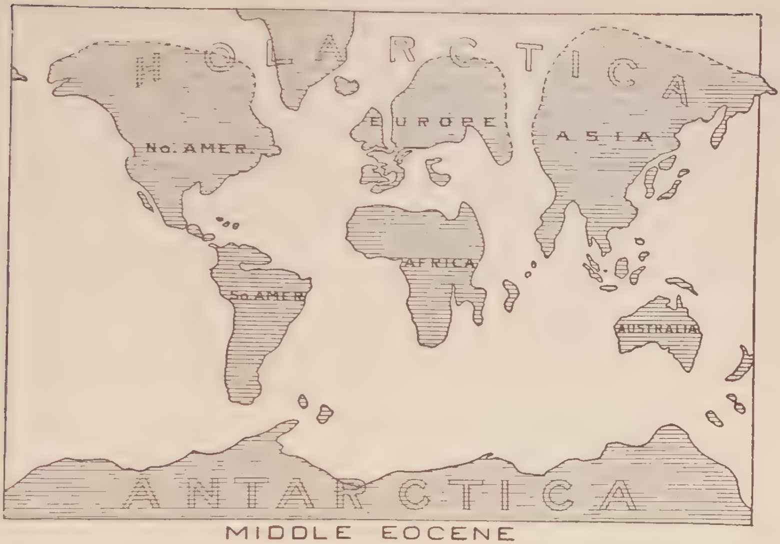


Fig. 561. — Map of the world in the Middle Eocene, showing the isolation of the continents and the conditions favorable for the development of provincial faunas. (After W. D. Matthew.)

Fig. 562. — The separation of Africa and South America from their neighboring continents caused the animals of the former to develop independently, while the union of Asia to North America permitted intermigration between these continents. (Afte W. D. Matthew.)

The effect of isolation upon the animal life depends somewhat upon the size of the region and the diversity of the topography. If the topography, climate, and vegetation are varied, a diversified mammalian fauna will arise to take advantage of every opportunity of securing food; and the body, limbs, and feet will become adapted to a great variety of conditions; some will become adapted for burrowing, some for life in the water, some for rapid motion, and some for tree life. The larger the region and the more diverse the conditions, the greater will be the variety of mammals that will result. When after long periods of isolation animals which, because of the physical conditions under which they lived or because of the fierceness of the competition with other forms, had become especially fitted for life, were able to migrate to other regions where for various reasons evolution had not been so effective in producing such successful types; the better fitted quickly possessed the new regions, either forcing the former inhabitants into subordinate positions or causing their extinction.

Fig. 563. — The continents, with the exception of South America, were broadly united during the Middle and Upper Miocene, permitting widespread migrations. (After W. D. Matthew.)

No better example of the effect of such isolation can be found than in Australia to-day, where only mammals of a low type (marsupials) occur. These Australian mammals are very different from those of other parts of the world, but are related to those that lived in Europe in the Mesozoic; types which with a few exceptions have long since been extinct in other continents. The natural inference is that Australia was isolated during the whole of the Tertiary epoch and that, because of the non-interference of the higher mammals, the marsupials have been able to develop there along their own lines, producing the kangaroo, the wombat, and the other animals peculiar to that continent.

The effect of isolation and migration on animal life is especially well shown in the history of Tertiary mammals.

Eocene Invasion. — The first, and perhaps most important Tertiary migration occurred at the very beginning of that epoch, as is shown (1) by the sudden appearance of true mammals which, though simple in structure, were already somewhat diversified, and (2) by their similarity in all parts of the world where found. The land connection, or connections, which permitted this migration from a center whose location is at present unknown, disappeared, perhaps by subsidence, and the continents of the Old and the New World were apparently again separated by broad seas for a long period of time (Fig. 561), permitting the life of the isolated regions to develop independently during the Eocene. A comparison of the life of the Middle and Upper Eocene shows that the odd-toed, hoofed mammals (perissidactyls) of Europe and North America differed in many respects, and that, although horses developed on the two continents, they were markedly dissimilar. The same dissimilarity is shown in the carnivores and rodents. During this period of isolation three new families made their appearance in America, the camels (p. 615), oreodonts (p. 619), and armadillos (p. 621); and the most striking of the Rocky Mountain Eocene mammals (Amblypoda) were probably extinct in Europe before the Upper Eocene, but did not become extinct in America until near the close of the Upper Eocene. The resemblance that existed between the mammals of the two continents is only that of descent from similar ancestors.

Oligocene Invasion. — The simultaneous appearance in Europe and North America (Fig. 562) of new families of mammals of a decidedly more modern type than those of the Eocene, points strongly to their evolution in some region separated from both continents for a long period, and united to them at approximately the same time by renewed land connections. It should not be inferred from the above that the intermigration was so great as to make the life of the two continents identical at the beginning of the Oligocene, for this was far from being the case.

Following the period of land connections at the beginning of the Oligocene, the Old and the New World were again isolated and independent evolution was permitted.

Miocene African Invasion. — The similarity of the life of Europe and of North America indicates that these continents, as well as the East Indies, were united during the Miocene (Fig. 563); but the dissimilarity of that of South America and Australia shows that these southern continents were separated from the others. The appearance in the Lower Miocene of Africa and Europe of ancestral elephants whose development had been taking place in Africa or some adjoining region, during the earlier portion of the Tertiary, shows that these continents of the Old World were then united, for the first time perhaps, since the early Eocene. The mastodons and rhinoceroses migrated to America at this time, and other tribes unquestionably came with them. They are believed to have reached here by way of the Alaskan land connection. These strangers had little effect on the life of the New World, as is shown by the development in America of its own pigs, oreodonts (p. 619), deer (p. 618), antelopes (p. 619), camels (p. 615), horses (p. 608), etc. Although the continental connections were well-established between Europe, Asia, Africa, and North America in the Miocene and continued throughout the epoch, permitting the spread into North America of mastodons, rhinoceroses, and probably other mammals, yet many of the important races of the New World — such as the camels, llamas, ancestral horses, and ancestral American deer — were confined to this continent; and animals equally characteristic of the Old World — true rhinoceroses, African and Asiatic monkeys, bears, lynxes, foxes, hyenas, true antelopes — are not known to have migrated to North America at this time.

Pliocene South American Invasion and Intermigration between the Old and New Worlds. — With the connection of South America and North America in the Pliocene, all of the continents of the world with the exception of Australia were united, and widespread migration occurred.

South America seems to have been isolated from the rest of the world from early Eocene times until the Pliocene. Its fauna, before the Pliocene connection with North America was established, was comprised of (1) marsupials resembling, in a marked degree, those of Australia to-day, and (2) true mammals differing greatly from those that had been developing in North America. The explanation of this peculiar fauna is probably to be found (1) in the absence of all true carnivores (the cat and dog family having, so far as is known, failed to send any Eocene representatives there), and (2) in the small variety of ancestral forms from which the fauna developed. This small number of ancestral true mammals indicates that the Eocene Central American connection had been of brief duration. These South American ancestral forms came from North America, or from Australia by way of the Antarctic Continent, or from both.

During the period of separation, several families of strange hoofed mammals were evolved to take advantage of the varied physical conditions, some of which (Litopterna) were odd-toed, with bodily proportions resembling those of the horse and llama. In this family the third toe was always the largest, and in some species the evolution of the foot had been carried to the one-toed stage, producing a foot similar to that of the horse. They were, however, inferior in brain and teeth to the even and odd-toed herbivores of North America.

The most remarkable development occurred in the sloth tribe (edentates) (p. 670), in which huge forms, elephantine in size but of different proportions, some of which were covered with armor, were numerous and conspicuous.

Rodents of the porcupine type and monkeys were abundant during the Tertiary and are living in South America to-day.

With the joining of North America and South America, an intermigration of animals from the two continents began. Horses, llamas, deer, mastodons, tapirs, members of the cat and dog family, and others invaded South America; and at the same time the giant sloths and other South American forms moved north. The result was to be expected. Not all of the families of North American mammals found a home in South America, either because they did not migrate there or because the conditions were unfavorable for their existence; but, as a rule, these immigrants from the north in which brain and limb had been highly developed as a result of the severe struggle with highly specialized carnivorous enemies, as well as because of the competition with other herbivorous forms, soon crowded out the more conspicuous but less highly developed indigenous animals. To-day the most conspicuous South American animals are those whose ancestors reached that continent in the Pliocene, although many characteristic ancient forms, such as the armadillo, are numerous.

Not only did the North American mammals invade South America, but a similar invasion in the opposite direction was going on at the same time. These immigrants, however, failed to establish themselves permanently, although they probably lived on in their new home for some time, as the presence of their remains as far north as Oregon shows. Their extinction before the Pleistocene was due either to the competition with the higher forms or to the cold of the Glacial Period, but probably to the former.

Duration of the Tertiary. — Because of the fact that the Tertiary rocks are, with the exception of the Pleistocene, the last deposited, some evidence of the duration of the period is at hand which is not available in estimating the length of former periods. The most important means which can be employed are the following:

(1) Biologists are generally agreed that the time necessary for the evolution of modern mammals from the generalized ancestors of the early Eocene was very long. For example, the highly specialized modern horse could not have been evolved from the little Eohippus with his four-toed foot, simple teeth, and carnivorous-like body, in tens of thousands, or hundreds of thousands of years; but a much greater length of time must have been required.

(2) Again, as in other periods, we can gain some idea of the vastness of Tertiary time by a consideration of the mountain ranges which had their birth and principal growth during the period. At the beginning of the Tertiary, Switzerland was probably a comparatively flat plain where the lofty peaks of the Alps now stand; and the grandest mountains of the world, the Himalayas, were not raised until about the middle of the Miocene. It is impossible to state how long, in years, this great deformation required, but it is evident that an almost inconceivable length of time was necessary.

(3) Since the close of the Eocene the Grand Canyon region has been elevated 11,000 feet; and the Colorado River has been able to carve its way through limestone, sandstone, and granite to a depth of 6500 feet.

(4) The most approved method of estimating geological time is by the maximum thickness of the sediments deposited during the period (p. 417). Upon this basis the duration of the period has been variously estimated at from 3,000,000 to 4,000,000 years, with the former estimate more generally accepted than the latter.

CHAPTER XXII

QUATERNARY

The last great period of the earth's history — the Quaternary — may be considered as beginning with the initiation of extensive sheets of ice in the northern hemisphere. It is divided as follows:

Quaternary	*Recent, Post-Glacial or Human.* Since the disappearance of the continental ice sheets.
	Pleistocene (Greek, *pleistos*, most, and *kainos*, recent) *or Glacial.* Extending from the beginning of glaciation until the final disappearance of continental glaciers.

CHANGES AT THE CLOSE OF THE TERTIARY

Three important changes at the close of the Tertiary should be noted.

(1) **Elevation.** The later Pliocene and early Quaternary was a time of elevation, during which the continents stood higher than now, and broad land connections existed, permitting migration between the continents. On the Atlantic coast the Pleistocene elevation has been variously estimated at from a few hundred to a few thousand feet. Evidence is at hand of an elevation of 1500 feet in southern California, of 3000 to 6000 feet in the Sierra Nevadas, 1500 feet in Oregon, and of an even greater raising of the land in British Columbia. In the West Indies, Panama, and South America, observations point to a higher level of the land than now during portions of the epoch. An upward movement increased the height and extent of Europe, so that at the time of maximum elevation Great Britain was a portion of Europe, and Europe was united to Africa by broad land connections across Gibraltar and through Italy by way of Sicily. After a time elevation ceased, and a subsidence began which first separated Ireland from Wales and later from Scotland, and finally isolated Great Britain. The land connections with Sicily,

which joined Europe and Africa, and that at Gibraltar also disappeared. It seems probable that the separation of Japan and the Philippine archipelago occurred in post-glacial times.

(2) **Glaciation.** — The gradual refrigeration of the climate at the close of the Tertiary culminated in the Pleistocene. The cause, or causes, which produced this marked decrease in temperature will be discussed later (p. 660).

The lowering of the temperature resulted in the accumulation of snow and ice to form great ice sheets, several hundreds to several thousands of feet thick, which spread over 6,000,000 to 8,000,000 square miles of the earth's surface, especially in the northern hemisphere. Although this is an important event in the world's history, it should be remembered that it is not unique, since extensive glaciation occurred in the Permian (p. 505) as well as in Pre-Cambrian times (p. 398), and possibly at other periods. It should also be noted that these earlier ice invasions have not been considered of sufficient importance to form a basis for a further subdivision of these earlier periods. Why, then, is the separation into Tertiary and Quaternary made? It is because the event was so recent (geologically) that the evidences of glaciation are widespread and conspicuous, since sufficient time has not yet elapsed to obliterate them by erosion and weathering, and also because the indirect effect upon man has been of great importance (p. 662).

(3) **Changes in Life.** — The least important change between the periods is in the life. As far as this is concerned, the Quaternary might almost equally well be considered a continuation of the Pliocene. At the beginning of the period nearly all living species of mollusks were in existence, and most of the species of living mammals, but during the Pleistocene there was a gradual disappearance of many mammals, such, for example, as the mammoth, mastodon, woolly rhinoceros, and saber-toothed tiger. After the Tertiary there was no longer a mingling of tropical and subtropical plants with temperate and Arctic plants (p. 634); but, possibly as a result of the migrations forced on them by the climate, they became adapted to special habitats.

REFERENCES FOR CHANGES AT THE CLOSE OF THE TERTIARY

Chamberlin and Salisbury, — *Geology*, Vol. 3, pp. 483–490.
Willis and Salisbury, — *Outlines of Geologic History*, pp. 265–275.

Distribution of the Ice Sheets

The great event of the Pleistocene was the accumulation of vast continental glaciers.

1. **Other Continents.** — As a result of the increasing cold the whole of northern Europe (Fig. 564) was buried under an ice sheet of great thickness, which filled up the basins of the Baltic and North seas and spread over Scotland and the greater part of England.

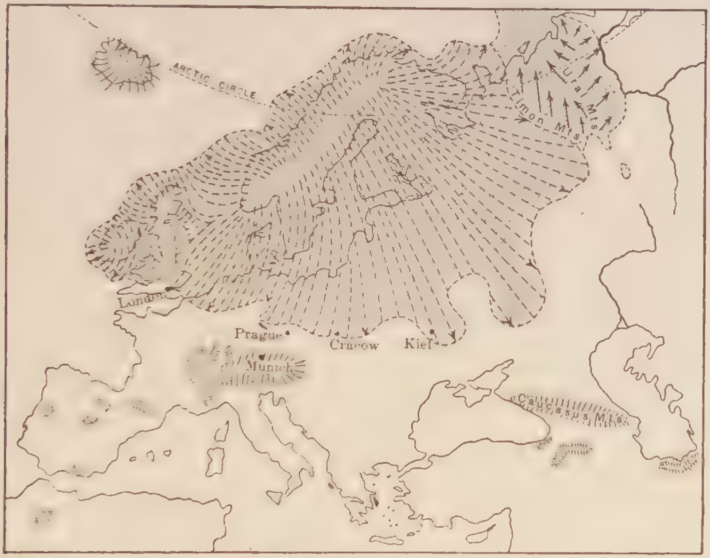


Fig. 564. — Map of Europe during glacial times. The area covered by glaciers is shaded, and the direction of the movement of the ice is indicated by arrows. (After J. Geikie.)

The Alps and Pyrenees were covered by great snow fields and glaciers which stretched over the neighboring lowlands, and even the island of Corsica had glaciers. In the southern hemisphere and in the tropics glaciers appear to have existed where none are now, and our present-day glaciers are insignificant remnants of those of Pleistocene times. One interesting exception to the general glaciation of the northern portion of the Old World was the absence of glaciers in Siberia, where, even at the present, a portion of the country has a mean temperature of five degrees, the soil is permanently frozen to a depth of several hundreds of feet, and Arctic conditions prevail over large areas. The absence of glaciers is now, and probably was then, due to the deficient precipitation, which makes an accumulation of snow impossible.

2. **North America.** — North America (Fig. 565) was more extensively affected by glaciation than any other part of the world, about 4,000,000 square miles being covered by ice at the time of its greatest extension. Two peculiar features are especially striking in the distribution of the North American ice sheets: (1) the greatest extent of ice was in the low regions of the northeast, instead of in the high mountains of the west and northwest; and (2) the northeastern portion of the continent, rather than the northern, was the scene of maximum glaciation, even Alaska being largely free from ice.

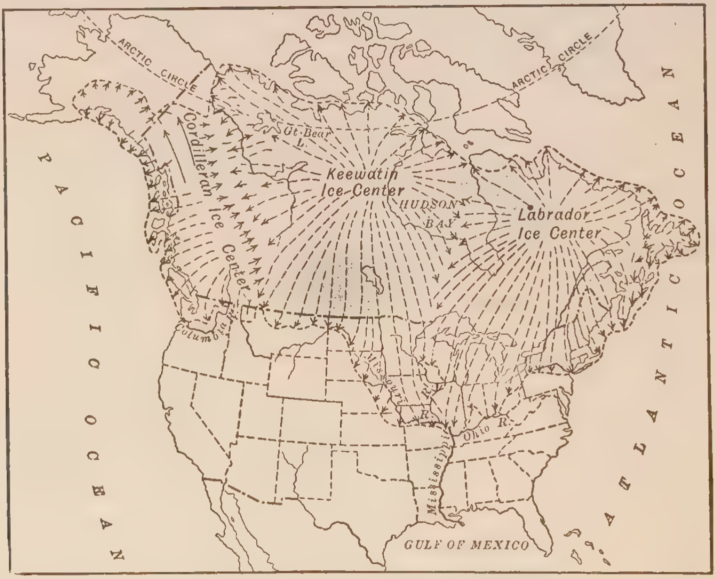


FIG. 565. — Map of North America, showing the area covered by ice at the stage of maximum glaciation, and the centers from which the ice moved. The arrows show the directions of ice movement.

The great ice sheets moved in all directions from three great centers and probably to some extent from other smaller ones, as is proved by the direction of the striations on the underlying rocks, and the courses along which the bowlders were carried. These three great centers of radiation were: (1) that situated in Labrador (the Labradorean); (2) that just west of Hudson Bay (the Keewatin); and (3) that in the western mountains (the Cordilleran). The greatest extent of the Labradorean ice sheet was to the southeast, where it stretched 1600 miles south of the center. There was also a movement north from this center, but it is not known to have been nearly so extensive. This ice sheet, in its greatest expansion, crossed the Ohio River into Kentucky, and extended into southern Illinois.

The Keewatin ice sheet extended almost as far southward as the Labradorean, its front at one time being in Kansas and Missouri, about 1500 miles from its center. The movement of the Keewatin ice sheet is remarkable since, beginning in a low, flat region, which is now semiarid, the ice moved upgrade into the United States. This is more astonishing when we find that the Cordilleran sheet, starting from the lofty mountains of western North America, apparently failed to move beyond their foothills. The Cordilleran ice sheet should, perhaps, be considered as the product of the confluence of mountain glaciers, spreading out as they reached lower and less rugged ground, much as do some of the Alaskan glaciers to-day.

Besides these great centers of ice movement, large local glaciers accumulated on the mountains of the western United States, where they were vigorous for many years, as is shown by the cirques (p. 143), moraines, rock basins, and other evidences of glaciation common throughout the high mountains of the west. This is well seen on the topographic maps of Montana, Wyoming, Colorado, and neighboring states.

REFERENCES FOR GLACIATION IN NORTH AMERICA

CHAMBERLIN AND SALISBURY, — *Geology*, Vol. 3.
GEIKIE, A., — *Textbook of Geology.*
GEIKIE, J., — *The Great Ice Age.*
WRIGHT, G. F., — *The Ice Age in North America.*
WRIGHT, W. B., — *The Quaternary Ice Age.*

DEVELOPMENT OF THE ICE SHEETS

The great ice sheets (with the probable exception of the Cordilleran center) did not begin as mountain glaciers which by their coalescence became one great glacier, but were the result of the gradual accumulation of snow in the north, due to the lowering of the temperature (p. 660).

Thickness of Ice Sheets at Center. — It has been held that the great ice sheets were several miles thick at the various centers, from which points they gradually thinned toward the margins. A study of existing Greenland and Antarctic glaciers shows that such is not now the case, but that the thickness of the ice not far from the margin is practically the same as that of the interior, the surface of which is a comparatively level plain.

The slope of the sides of the tongues of ice that reached down ravines of the Allegheny River somewhat beyond the margin of the main sheet varied from 100 to 130 feet a mile, and the average slope of the ice lobe of the Hudson valley has been estimated to have been 25 to 30 feet a mile. Even the smaller of these figures would make an enormous thickness for the ice sheets at the centers, if the slopes were uniform. Since the ice in Illinois is known to have reached 1500 to 1600 miles south of the center of accumulation, an average slope of 25 feet a mile would, on this basis, give a thickness of about eight miles at the center. It is probable, however, that the slope was not nearly so steep some distance back from the margin. When this is taken in connection with the fact that the thickness of the ice near the margin was probably approximately the same as that at the center, a much less depth is obtained than on the former estimates. Upon any basis, however, the thickness must have been great. In New England, for example, the ice was so thick that it passed over the Green Mountains where they are 3000 to 5000 feet high, in a course diagonal to their general direction, showing that such a mountain chain made "scarcely a ripple on the surface." (Tarr.)

GLACIAL AND INTERGLACIAL STAGES

The Glacial Period was made up of a number of advances of the ice and corresponding recessions when the ice either entirely, or largely, disappeared from the northern hemisphere. The duration of the various glacial stages was long, and that of the interglacial stages so extended as to permit trees and plants to clothe again the glaciated regions. The proofs of distinct ice sheets (Fig. 566), separated by long intervals, when the land was free from glaciers and

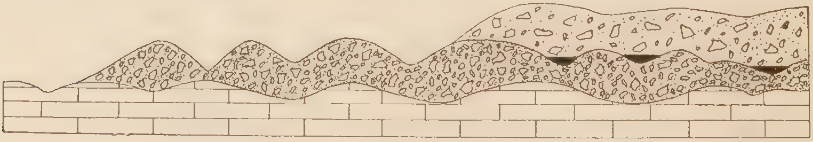


FIG. 566. — Diagram showing the proof of successive ice sheets. Resting upon the lower till sheet and underlying the upper are ancient peat bogs (solid black). The erosion of the older (lower) drift where exposed is much further advanced than that of the younger (upper). The composition of the drift sheets differs also.

even warmer than at present in the same regions, are conclusive. The drift of the earlier glacial stages, where it has not been covered by more recent drift, differs from the latter in a number of particulars: (1) the drainage of the surface is mature, being in this respect in marked contrast to the immature drainage of the most recent drift, with its lakes and marshes; (2) the bowlders of the older drift sheets are found to be different from those of later drifts, showing that they were brought by ice sheets that moved in a somewhat different direction; (3) the bowlders of the older drift are, moreover, much weathered, so that even granite bowlders can sometimes be crumbled in the hand, and the clay is deeply oxidized and the lime largely leached out. (4) Deeply eroded surfaces, covered with peat or ancient soils (Fig. 567) occur, underlying more recent drift. The most satisfying proof is found in two sections, one in Iowa and the other near Toronto, in which stratified deposits containing fossils rest upon old, weathered till and are, in turn, overlain by younger drift.

The recognized glacial stages in America and Europe are:

NORTH AMERICA	IN THE ALPS
Postglacial	Iron Bronze Neolithic
Wisconsin	Younger Paleolithic man (Cro Magnon) in Europe Würm
Interglacial (Peorian) Main loess deposition (Iowan)[1] Interglacial (Sangamon)	Older Paleolithic man (Neanderthal) in Europe Third Interglacial
Illinoian	Riss
Second Interglacial (Yarmouth)	Second Interglacial Heidelberg man in Europe
Kansan	Mindel
First Interglacial (Aftonian)	First Interglacial
Jerseyan (Nebraskan)	Günz

[1] There is some doubt as to the interpretation of the Iowan.

Characteristics of Former Drift Sheets. — It will not be advisable to discuss these glacial stages in detail (see references). The different stages varied in duration, in the character of the material deposited, and in the extent of the glaciation. The deposits of the Kansan ice sheet, for example, contain little stratified drift, indicating that stream action was of little importance. This is surprising, since the melting of great masses of ice naturally carries with it the idea of flooded streams and great deposits of stratified drift, such as resulted

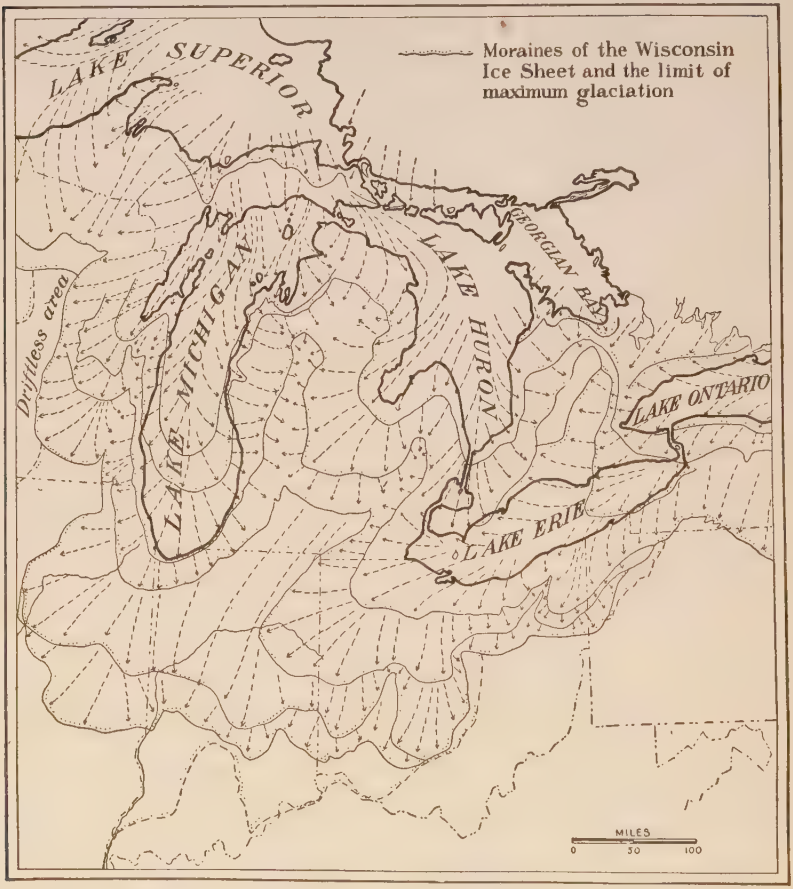


FIG. 567. — Map showing the moraines and the direction of the ice movement (shown by arrows) of the last continental ice sheet. The lobate character of the moraines is very pronounced. The "driftless area" was not covered by the ice. (Modified after Leverett and Taylor.)

from the last ice sheet. The effect of the last recrudescence of glaciation in the Wisconsin stage is best known, since its deposits cover the earlier drifts. It seems probable, moreover, that the surface of the last drift had a relief stronger, originally, than that of any of the former ice sheets. One marked feature is the lobate form of the moraines which occur in a succession of crescentic belts (Fig. 567).

History of the Great Lakes

There is general agreement that the Great Lakes were not in existence immediately previous to glacial times. This belief is based upon the fact that the region now occupied by them had been subjected to erosion so long that any lakes which might at some time have been in existence must have been destroyed by filling or the cutting down of their outlets. It is probable that in preglacial times the region in the vicinity of the Great Lakes was not unlike that of central and eastern Tennessee, Kentucky, and southern Indiana, where the weak rock formations are marked by lowlands, and the more resistant by highlands.

Preglacial Drainage. — The precise course of the preglacial drainage of this region is yet to be determined, but the evidence indicates that the St. Lawrence River was not as now the channel through which it flowed to the ocean. At that time, indeed, the head of the St. Lawrence River may have been in the vicinity of the Thousand Islands. Well borings in Michigan and Indiana have revealed the fact that ancient, drift-filled valleys of great depth lead towards the south, giving strong support to the supposition that the preglacial drainage was southward to the Ohio and Mississippi, instead of to the east. In fact, at the present time a lowering of the land a few feet at the southern end of Lake Michigan would turn the drainage to the Mississippi Valley.

Origin of the Basins. — The basins of the Great Lakes are lowlands which have been modified in several ways: (1) by drift deposition which has not only blocked up the valleys leading south, but has also increased the height of the divides by terminal moraines; (2) by glacial erosion, though whether the glaciers accomplished more than the removal of the weathered rock and soil is a mooted question; all will concede, however, a deepening to this extent at least; (3) by a depression of the region at the north as a result of the weight of the ice. Since the disappearance of the ice sheets the land at the north has been slowly rising, as is shown by the beach lines of the ancient lakes which are now higher at the north than they are further south — in some cases 400 feet or more. The surfaces of the lakes are held up by rock and drift barriers to levels several hundreds of feet above their rock beds, while the bottoms of all the lakes, except Lake Erie, are below sea level.

Great Lakes Stages.[1] — The Great Lakes had their inception when the ice sheet had retreated across the higher land which turns some of the water to the north and some to the south. The melting waters being prevented from flowing north, accumulated between it and the ice front, gradually enlarging upon the further recession of the ice. At first there were doubtless many small lakes which had temporary outlets to the south. As the ice retreated still further these lakes coalesced into larger ones. The brief and incomplete history of the Great Lakes which is given below has been learned from a study of the beaches, sand bars, deltas, and outlets made at former lake levels.

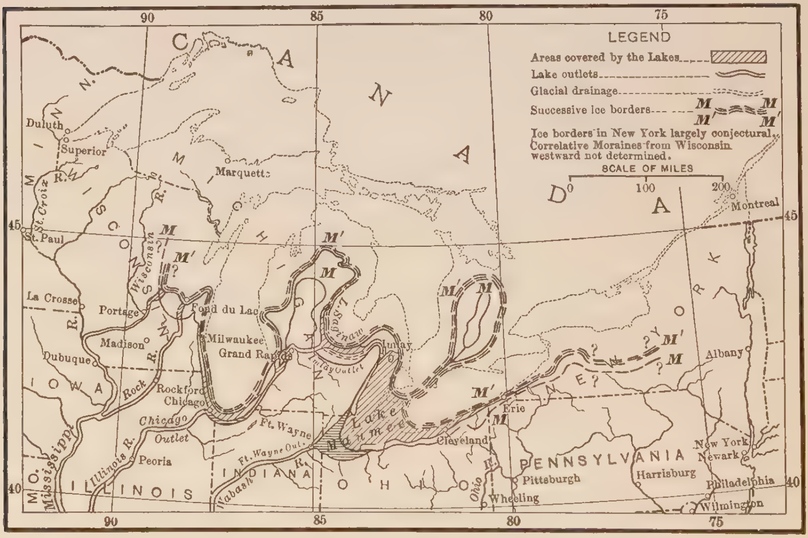


FIG. 568. — An early (*first*) stage in the history of the Great Lakes. (After Taylor and Leverett.)

The history of the Great Lakes may be considered as beginning after the ice had retreated to such an extent that a large lake (glacial

---

[1] Taylor, F. B., — *The Glacial and Postglacial Lakes of the Great Lake Region:* Smithsonian Rept., 1912, pp. 291–327.

Lake Maumee) came into existence near the western end of what is now Lake Erie, and which emptied through the Wabash River into the Mississippi River. This may, for convenience, be called the *first stage* (Fig. 568) in the history. In the *second stage*, the ice front had retreated to such an extent that a greatly expanded Lake Erie (glacial Lake Warren) was formed which emptied through the Illinois River into the Mississippi River. Upon a further retreat of the ice, a *third stage* (Fig. 569) was inaugurated, with the resulting formation of three Great Lakes with three outlets; Lake Superior (glacial Lake Duluth) discharging over the divide at Duluth through the St. Croix into the Mississippi River, Lake Michigan (glacial Lake Chicago) through the Illinois River as before, and lakes Erie and Huron (glacial Lake Lundy) through the Mohawk River in New York to the Hudson River. In the *fourth stage* (Fig. 570) the region of the Great Lakes was entirely uncovered with the exception of the St. Lawrence River; at this time the present lakes Michigan, Superior, and Huron were greatly expanded to form a lake which covered a greater area than that occupied by all of the present Great Lakes. This lake (named Lake Algonquin) discharged through the Mohawk River to the Hudson and probably also for a time through

FIG. 569.—A (*third*) stage, in which three Great Lakes with separate outlets were formed by the further retreat of the ice front. (After Taylor and Leverett.)

FIG. 570. — In this (*fourth*) stage the Great Lakes had their greatest area, forming Lake Algonquin. The outlets were the Mohawk and Illinois rivers. (Modified after Taylor and Leverett.)

FIG. 571. — A (*fifth*) stage with the drainage through the Ottawa River. A lowering of the region resulted in the extension of the sea into the St. Lawrence valley and Lake Champlain. (After Taylor and Leverett.)

the old Chicago outlet. During an early part of the stage Lake Huron probably emptied into Lake Erie, but later, when the ice front had melted back farther to the north, drained through the Trent River in Canada to Lake Ontario (named Lake Iroquois), reducing Lake Erie to such an extent that the amount of water flowing over Niagara falls was probably not greater than that now pouring over the American falls. As the land was uplifted in the north (as the weight of the ice was removed), the drainage of Lake Huron was again discharged over Niagara Falls. The *fifth stage* (Fig. 571) began with the opening of an eastern passage along the ice border into the Ottawa valley, which lowered the surface of the lakes (forming Lake Nipissing). The drainage passed through this outlet until the elevation of the land on the north was sufficient to send the waters into their present course. The beach lines of this fifth stage rise at the north (are higher at the north than at the south), showing an uplift of 100 feet at the head of the Ottawa River since it was abandoned.

There seems little doubt that at each advance and retreat of the ice, during the different stages, lakes were formed in somewhat the same position as at the close of the last ice (Wisconsin) invasion. The proof of such lakes is not abundant, but is indicated by the sandy character of the drift in the moraines at the south end of Lake Michigan, the sand having probably been obtained by the ice from the deposits of a former Lake Michigan.

REFERENCES ON THE HISTORY OF THE GREAT LAKES

CHAMBERLIN AND SALISBURY, -- *Geology*, Vol. 3.
TARR, R. S., — *Physical Geography of New York State.*
TAYLOR, F. B., — *The Glacial and Postglacial Lakes of the Great Laké Region:* Smithsonian Rept., 1912, pp. 291–327.

The Champlain Subsidence. -- The fifth stage (Fig. 571) of the Great Lakes was coincident with a great subsidence of the northeastern Atlantic coast, which permitted the sea to spread over the St. Lawrence valley, Lake Ontario, Lake Champlain, and the Hudson River, thus making New England an island.

The sediments carried into these bodies of water at that time contain marine shells and even the skeletons of whales, one of which was found in a Lake Champlain terrace, and another in the Ottawa valley. The terraces near Montreal which are 600 feet above the sea, those of Lake Champlain which are 500 feet at the northern end and 400 feet or less at the southern end, and those of Maine which are 200 or more feet in height, show both the amount of sinking in that epoch and the differential uplift since then.

OTHER PLEISTOCENE LAKES

Lake Agassiz. — The Red River valley of Manitoba, North Dakota, and Minnesota, so remarkable for its fertility as well as for its flatness, is the result of a glacial dam which prevented the usual drainage through the Red River to the north, and produced a great lake (Lake Agassiz) which discharged by way of the Minnesota River into the Mississippi. On its bottom the silts carried in by the streams were deposited, making a surface as flat perhaps as any on earth. Upon the retreat of the ice, drainage to the north was permitted, and the lake disappeared. At its greatest extent this lake had a larger area than that of the present Great Lakes combined.

Lake Bascom. — In rugged regions the ice sheet formed many temporary lakes, a rather remarkable example of which is to be found in northwestern Massachusetts, where a lake (Lake Bascom) first stood at an elevation of 1100 feet above the sea, the level of the lake being determined by the pass (col) through which the water was discharged. As the ice retreated, lower passes, approximately 1000, 900, 700, and 600 feet above the sea, were found; and the lake was finally drained when the present outlet — the Hoosic River — was uncovered.

FIG. 572. — Map showing the position of Lake Bonneville on the east and Lake Lahontan on the west. The relative size of Great Salt Lake is indicated.

Great Basin Lakes. — In some semiarid regions not covered by the ice sheet the climate of the Pleistocene seems to have been moister than at present and previous to glacial times. This is brought out by a study of the Great Basin region of Utah and Nevada. Great Salt Lake is a small remnant of a Pleistocene lake (Lake Bonneville), which was many times larger (Fig. 572), discharging at one stage by a northern outlet to the Pacific. This lake (Lake Bonneville) at its maximum was 1000 feet deep and covered an area of 17,000 square miles. Terraces marking former levels of the lake are conspicuous features of the landscape, as seen from Salt Lake City and other portions of the basin. A return to an arid climate caused the shrinkage of the lake to its present area and maximum depth of only 50 feet. The salt lake which doubtless formerly existed there in preglacial times was gradually freshened as the lake level was raised, and became entirely fresh when the excess water flowed through the outlet. When the climate again became drier, the lake shrank, and all of the soluble salts of the larger lake, as well as those brought into the basin since that time, have accumulated to form the present exceedingly saline waters.

Further west in the same basin were other lakes (Lake Lahontan) which, however, were not as large as Lake Bonneville, although of considerable extent.

REFERENCES ON PLEISTOCENE LAKES

Berlin-Greylock and Hoosick-Bennington Folios, U. S. Geol. Surv.
Gilbert, G. K., — *Lake Bonneville:* Mon. U. S. Geol. Surv., Vol. 1, 1890.
Textbooks of Geology.
Upham, W., — *The Glacial Lake Agassiz:* Mon. U. S. Geol. Surv., Vol. 25, 1896.

Loess

In the Mississippi basin, especially in Illinois, Iowa, Nebraska, and states to the south, are extensive areas of a deposit (loess) intermediate between fine sand and clay (p. 52). The fact that it contains angular, undecomposed particles of calcite, dolomite, feldspar, hornblende, mica, and magnetite indicates that loess was derived from the finely ground rock flour of the glaciers. Pebbles, with the exception of lime and iron concretions, are absent, except at the base of the deposits. The most striking characteristic of loess is its ability to form vertical cliffs, a feature which can best be seen in railroad cuts and along stream courses.

One peculiarity of its distribution is its independence of topography. Its thickness seldom exceeds 50 feet, while 10 feet is more common. Loess occurs on the drift, between drift sheets, and even beyond the limit of the drift sheets.

The question of the origin of this widespread deposit has given rise to much discussion, but to a large extent the aqueous theory, *i.e.*, that loess is a deposit that was laid down in standing water, has been replaced by the eolian. According to the latter, glacial streams, heavily loaded with rock flour, spread silt upon their flood plains, exposing it to the action of the winds, which caught it up and redeposited it on the adjacent uplands, where after its deposition it was held by the vegetation. A similar deposit is forming to-day on the western plains, where loess-like dust is held by the grasses and is slowly building up portions of the surface. If the above explanation is correct, the presence of such extensive areas of loess indicates aridity during some of the glacial or interglacial stages, since if the climate was moist, the action of the winds would be inconsiderable.

REFERENCES ON LOESS

CHAMBERLIN AND SALISBURY, — *Geology*, Vol. 3; (for references to literature).
WRIGHT, G. F., — *The Ice Age in North America*, pp. 359–371.

DURATION

The difficulty of arriving at a definite conclusion as to the length of the Glacial Period, as expressed in years, is seen when the elements upon which such estimates must be based are analyzed. These are (1) the weathering and erosion of drift; (2) the time necessary for the climatic changes between the glacial and interglacial stages; (3) the amount of vegetable growth in interglacial stages; (4) the time necessary for the immigration of plants and animals. These all show that a long period of time must have elapsed, but afford little basis for an estimate in terms of years. (5) The time required for the advance and retreat of the ice sheets, however, affords something of a clue, since the rate of the advance and retreat of existing glaciers is known; but such estimates, at best, are subject to wide variations, depending upon the rate used as a basis. This is well shown in the figures given by different investigators, which vary from 100,000 years (Upham), to 500,000 to 1,000,000 years (Penck). The former estimate, however, is evidently much too small.

The time which has elapsed since the beginning of the retreat of the last ice sheet is better known, because of other lines of evidence. These are (1) the time required for the retreat of the ice, and (2) the time necessary for the excavation of the Niagara (Fig. 573) and St. Anthony gorges, the present rate of the recession of these falls being known. When allowances are made for fluctuation in the volume of the rivers at different times after the ice had retreated so as to permit the streams to flow over their new courses, it is seen that 20,000 to 35,000 years must have elapsed since the cutting of the Niagara gorge began. For the recession of the St. Anthony Falls between 12,000 and 16,000 years seem necessary. To these estimates must be added the time required for the retreat of the ice from its terminal moraine to the Niagara and Minnesota rivers. For this 10,000 to 30,000 years more should be added. This, then, would give 20,000 to 80,000 years since the beginning of the retreat of the last ice sheet. It is evident upon comparing the weathering of the Wisconsin drift with that of older drifts that the time which has elapsed since the last ice sheet is a small fraction of some of the interglacial stages. This has led to the suggestion that perhaps we are now in an interglacial stage. It is interesting in this connection to note that the extent of the area at present covered by glaciers is one tenth that of the maximum glaciation.

Fig. 573. Outline map of a portion of the crest line of Niagara Falls, showing the recession of the brink during various intervals since 1842. (After Taylor.)

Marine postglacial clays in Sweden have furnished an interesting basis for determining the length of postglacial time. These clays have been deposited in regular layers, with different colors and composition, the same succession being repeated time after time. The layers laid down in summer are brown, due to oxidation, and thicker; those laid down in the autumn are darker as a result of the greater amount of organic matter, and thinner. Counting these layers (much as the age of a tree is determined by the rings), it is estimated that Stockholm was covered with ice only nine thousand years ago, and that the glaciers withdrew at a rate of 800 feet a year. The ice is believed to have receded from Ragunda, Sweden, only 7000 years ago.

Causes of Glaciation

Numerous theories have been offered to account for the refrigeration of the climate which resulted in the Glacial Period, each of which has elements of probability, but none of which, as at present worked out, is perfect. In the consideration of all of the theories discussed below, it should be borne in mind that the appearance of an ice sheet does not necessarily imply an extremely low average temperature. It has been estimated that a fall of 3° F. in the average temperature of the Scottish Highlands, and a fall of 12° in the Laurentian region of Canada would result in a glacial period for these regions.

1. **Elevation.** — The explanation of glaciation which naturally suggests itself is that the refrigeration was due to a great elevation of the land in the northern hemisphere, which so reduced the temperature that snow accumulated to form glaciers as it does now on high mountains. Those who hold this theory point to the evidence of an elevation of several thousands of feet as shown by the fiords on northern coasts. The objections to the theory are (1) that it is probable maximum elevation and maximum glaciation did not coincide in time; (2) that the elevation was not as great as once supposed; (3) that glaciation not only occurred in the northern hemisphere, but that mountain glaciers throughout the world were more extensive than now. (4) Moreover, this hypothesis would require a great elevation for the glacial stages and a corresponding depression for the interglacial.

2. **Astronomical.** — A theory which at one time had wide acceptance was offered by Croll and is known as "Croll's hypothesis." It is based upon (1) the variation in the eccentricity of the earth's orbit as a result of which the relative length of the summer and winter seasons changes (Fig. 574). When the eccentricity is greatest the earth is 14,000,000 miles farther from the sun in the one season than in the other. (2) By means of the precession of the equinoxes the winter of the northern hemisphere, which now occurs when the sun is nearest the earth (perihelion) (Fig. 574 *A*), is

gradually, in 10,500 years, brought around so as to occur when the earth is farthest from the sun (aphelion) (Fig. 574 *B*). The combined effect of (1) maximum eccentricity and (2) the precession of the equinoxes is to make the winters 22 days longer and 20° colder, and the summers 22 days shorter and hotter than now. The cold of the northern hemisphere would be further intensified by the diverting of some of the ocean currents to the south as the "heat equator" moved south. In the Atlantic Ocean, if the heat equator were farther south, the equatorial current would be turned southward by the wedge-shaped eastern coast of South America. The lowering of the temperature would be further increased if elevation occurred at the same time.

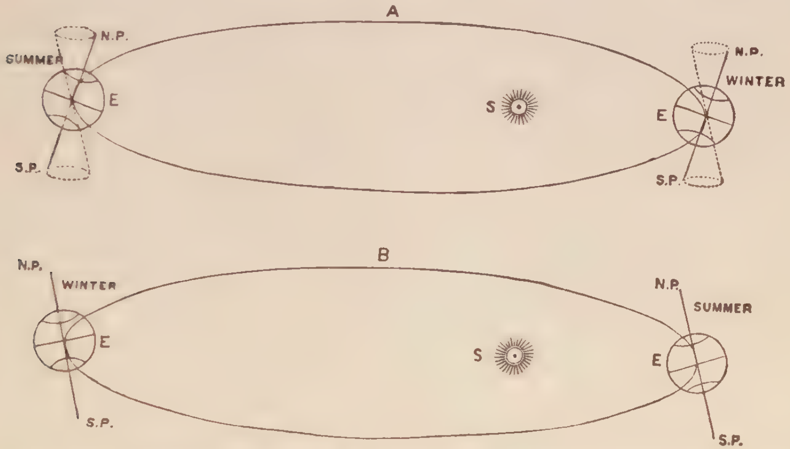


FIG. 574. — Diagram illustrating the astronomical theory of glaciation. *A*, diagram showing the relative positions of the earth and sun when the northern summer occurs in aphelion. This is the condition now. *B*, diagram showing the relative positions of the sun and earth when the northern summer occurs in perihelion. This condition favors glaciation, since the winters are longer and colder.

Some of the objections to the theory are (1) that the various ice invasions were not of equal duration as the theory requires; (2) that the duration of each glacial stage was greater than 10,500 years, in some cases many times greater; (3) that during the Pleistocene glaciation was greater in equatorial regions than now, where, according to the theory, there should have been little change of temperature.

3. **Atmospheric Hypothesis.** - An hypothesis based upon the varying amounts of carbon dioxide and water vapor in the atmosphere

has been favorably received, especially in America. Carbon dioxide and water vapor act much as does the glass in a greenhouse, *i.e.*, they form a thermal blanket which prevents the radiation of much of the heat derived from the sun. When the amount of one or both of these gases is diminished, the radiation increases, and the climate becomes colder. During periods of great elevation and continental extension, erosion would be greatly increased, and the withdrawal of carbon dioxide from the air would be rapid. This would be the case since carbon dioxide is consumed in large quantities by rocks in weathering. Such consumption, under conditions favorable to great erosion, may be in excess of the supply. Also, at times of great land extension the water surfaces are relatively small, and since less evaporation occurs there is diminution of the water vapor in the air. The elevation of the land at the close of the Tertiary favored the consumption of carbon dioxide, and the contraction of the oceans furnished less water vapor to the atmosphere than formerly. "By variations in the consumption of carbon dioxide, especially in its absorption and escape from the ocean, the hypothesis attempts to explain the periodicity of glaciation. Localization is attributed to the two great areas of permanent low pressure in proximity to which the ice sheet developed." (Chamberlin and Salisbury.)

REFERENCES FOR CAUSES OF GLACIATION

Chamberlin, T. C., — *An Attempt to Frame a Working Hypothesis of the Cause of Glacial Periods on an Atmospheric Basis:* Jour. Geol., Vol. 7, 1899, pp. 545–584; 667–685; 751–787.

Chamberlin and Salisbury, — *Geology*, Vol. 3, pp. 424–446.

Clarke, F. W., — *Data of Geochemistry:* Bull. U. S. Geol. Surv. No. 616, pp. 47, 48, and 143–147.

Croll, James, — *Climate and Time and their Geological Relations.*

Hobbs, W. H., — *Characteristics of Existing Glaciers.*

Wright, W. B., — *The Quaternary Ice Age*, pp. 293–325.

Effects of Glaciation

Glaciation benefited some regions and was harmful to others, but the former effects were, on the whole, greater than the latter. Among other benefits may be mentioned (1) waterfalls and rapids, which afford valuable water power; (2) lakes which not only afford means of transportation, but so ameliorate the climate as to permit the raising of fruits, such as peaches and grapes, which otherwise would not thrive. In addition to this, they beautify the region where they occur, affording for the city dwellers many attractive places for rest and recreation. (3) The bays of New England have for the most part been modified by glaciation. (4) Kames, eskers, and delta deposits furnish gravel for roads and for concrete where rocks suitable for these purposes were absent in preglacial times. (5) Deposits of clay suitable for the manufacture of brick are abundant in old glacial lakes and valleys. (6) Soils are sometimes more fertile and sometimes more sterile as a result of glaciation, but the balance is in favor of the former. The mixing of soils from different regions by glaciers is often beneficial, especially when they contain fine fragments of fresh rock which, upon weathering, furnish a constant supply of plant food. On the other hand, large areas overspread by glacial sand and gravel are comparatively worthless, and hilly regions are often covered with bowlders. Regions such as central Kentucky and the valley of Virginia, for example, would probably be injured were an ice sheet to pass over them, while others, such as the Piedmont of Virginia, might be benefited.

REFERENCES FOR THE EFFECTS OF GLACIATION

Chamberlin and Salisbury, — *Geology*, Vol. 3, pp. 358–412.

Von Engeln, O. D., — *Effects of Continental Glaciation on Agriculture:* Bull. Am. Geog. Soc., Vol. 46, 1914, pp. 241–264; 336–355.

Life of the Pleistocene

As the dinosaurs culminated in the Jurassic and Cretaceous, so the mammals attained their greatest size and variety in the Pliocene and Pleistocene. "The early and mid-Pleistocene life of North America is the grandest and most varied assemblage of the entire Cenozoic Period on our continent. It lacks the rhinoceroses of Europe, but possesses the mastodons, in addition to an array of elephants more varied and quite as majestic as those of the Old World. Great herds of large llamas and camels are interspersed with enormous troops of horses. Tapirs roam through the forests. True cattle (Bos) are not present, but imposing and varied species of bison are widely distributed. An element entirely lacking in Europe is that of the varied types of giant sloths, which were scattered all over the country, as well as the great armored glyptodonts in the south. Preying upon these animals are not only saber-toothed cats, but true cats, rivaling the modern lion and tiger in size." (Osborn.)

Our record of the life of the Tertiary and previous periods has been obtained largely from marine, lake, and blown-sand deposits. Deposits of these kinds also contain Pleistocene fossils; but, since Pleistocene animals were in existence but a comparatively short time ago, their remains are also found in superficial deposits, such as river terraces, peat bogs, frozen soils, ice cliffs, and cave deposits (Fig. 575), which, being easily destroyed by erosion, are seldom found in the older formations.

Marine Pleistocene deposits are not common, since the subsidence which followed the emergent condition of that epoch buried most of the sediments of the time beneath the sea. This is unfortunate, since, if a complete marine record were extant, we should have, as the ice sheet advanced and retreated, a succession of faunas and floras; the temperate life changing to arctic as the ice sheet advanced, and this, in turn, being replaced by the temperate, or even subtropical life (if the climate changed to that extent), when the ice again retreated. During each advance and retreat of the ice sheet a migration of the life to and fro would, theoretically, be recorded. Unfortunately, however, no such series of deposits has been discovered, either because ideal conditions did not exist in any one place, or because the deposits are inaccessible.

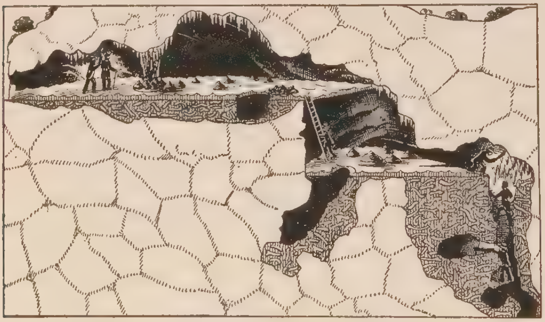


FIG. 575. — Gailenreuth Cavern, Germany.

Interglacial Deposits. — Fortunately two deposits are known which were laid down during interglacial stages. In one of these, near Toronto, Canada, the fossil beds were deposited upon the eroded surface of bowlder clay and were, in turn, eroded to some extent before the re-advance of the ice sheet which covered them with a layer of drift. The lower portion (Don) of this deposit yields plants which show that the climate was warmer in this interglacial stage than at present on Lake Ontario, being similar to that of Virginia to-day. This is indicated by the presence of the Judas tree (Cercis), the Osage orange (Maclura) and the papaw (Asimina). Besides these more typically southern trees, there are maples, spruces, oaks, elms, and hickories. In the upper portion (Scarborough beds) the fossil flora indicates a colder climate, showing that the ice sheet was again advancing.

A second occurrence of interglacial deposit (Aftonian) is in Iowa and yields the bones of a number of animals: elephants and mastodons, giant beavers (Castoroides), camels, horses, some dwarf and some perhaps larger than the domestic horse, and all of extinct species, giant sloths (Megalonyx), etc. This deposit is of especial importance since it gives some idea of the life of the first interglacial period and furnishes a clue to the age of the fossil deposits south of the limit of the ice sheet, since, if the fauna in any of these are the same as that of the above, it is probable that they lived at the same time.

North and South Migrations during Glacial and Interglacial Times. — We have seen that warm temperate plants, such as the papaw and Judas tree, lived in southern Canada during at least one interglacial period. The discovery of a fossil tamarack (larch) in Georgia, 480 miles below its present limit, shows that the Pleistocene climate of the southern states was colder at certain times than at present, and for a period sufficiently long to permit trees to grow. Walruses of a northern type lived on the coast of Georgia, and caribou and moose ranged into Pennsylvania and Ohio.

An interesting suggestion explaining the present migratory habit of birds is that it is due to the reduction in the temperature of the Arctic regions during late Tertiary and Pleistocene times. During the earlier Tertiary the comparatively uniform climate of the world would not necessitate any extended periodic movements, but the cold of the Glacial Period must have enforced prolonged migration, and periodic migration developed later. "During the waning ice period the areas offering a congenial home to a great multitude of birds became greatly extended, from which, however, they were driven by semi-arctic winters to seek favorable winter haunts farther southward."

Deposits beyond the Ice Sheets or Protected from Them. — (1) Caverns have been the greatest source of our knowledge of the mammalian life of the Pleistocene, the bones found in them having been brought there by floods or by beasts of prey which used the caverns as their lairs. The term "cavern" is used in the broad sense to include true caves, sink holes, and fissures. A section of the cave of Gailenreuth (Fig. 575), showing the bones embedded in clay and the whole covered by a stalagmitic crust, is typical of many European bone caverns. Sometimes, however, there is more than one stalagmitic crust. The number of individuals and species represented by the bones found in some of these caves is remarkable. In the Gailenreuth cave the remains of 800 cave bears were found; from one in Sicily 20 tons of hippopotamus bones were taken. A cave in Pennsylvania (Port Kennedy), 60 to 70 feet deep, has yielded 64 species of mammals, of which 40 are extinct, among them being giant sloths, tapirs, mastodons, and saber-toothed tigers. In a California cave, horses, camels, ground sloths, mastodons, and other extinct forms have been identified.

Caves were doubtless inhabited by the land animals of the Tertiary and other periods, but as caves have a relatively short life, they and their contents are rarely preserved in the older formations.

(2) Marshy ground in the vicinity of springs has often preserved many fossils, since at such places carnivores frequently kill their prey when the latter are coming down to drink; and in times of drought the animals of the region congregate about the water holes, where they often die in large numbers. Many also are doubtless mired in wet seasons. One of the most famous of such deposits (Big Bone Lick, Kentucky) has yielded 100 specimens of mastodon, 20 specimens of elephant, as well as bisons, musk oxen, and other animals.

(3) An asphalt deposit (Fig. 576) not far from Los Angeles, California is remarkable, not only because unusual, but also because of the number of specimens preserved in it. In the early stages of the accumulation of the asphalt, the gummy surface apparently acted as a trap for unwary animals; where there were pools of water, aquatic birds of many kinds were entrapped in the soft tar about their margins; while land birds and smaller mammals were ensnared in attempting to reach the water. Sloths, mammoths, horses, camels, saber-toothed tigers, together with many birds, among which is a fossil peacock, are only a few of the numerous species already identified.

(4) Wind-blown sand and volcanic dust have covered and preserved skeletons which have since been uncovered and studied.

Difficulty is experienced in determining to what portion of the Pleistocene the deposits not found between sheets of drift belong, but four "zones," or subdivisions, of which certain animals are characteristic, have been recognized.

Deposits on the Last Drift. — The peat bogs which rest upon the drift of the last ice sheet (Wisconsin) have yielded a number of mastodon and mammoth skeletons. One mastodon found at Newburg, New York, had its legs bent under the body and the head thrown up, evidently in the very position in which it was mired. The teeth were

Fig. 576. — Pleistocene tar pool near Los Angeles, California, with entrapped animals. The elephant and wolves were caught, and the saber-toothed tiger is about to suffer the same fate. (After Prof. W. D. Scott, *History of Land Mammals.*)

still filled with the half-chewed remnants of its food which consisted of twigs of spruce, fir, and other trees.

REFERENCES FOR THE LIFE OF THE PLEISTOCENE

Geikie, J., — *Antiquity of Man in Europe.*

Matthew, W. D., — *The Asphalt Group of Fossil Skeletons:* Am. Museum Jour., Vol. 13, pp. 291–297.

Osborn, H. F., — *Age of Mammals*, pp. 467–480, 487, 498.

Scott, W. B., — *A History of Land Mammals in the Western Hemisphere*, pp. 29-49.

Vegetation. — The vegetation of the Pleistocene is a continuation of that of the Tertiary, and aside from the extinction of a few species little change is noticed. Some minor effects of glaciation on vegetation are, however, interesting. It is found, for example, that the number of genera of trees in Europe (33 genera) is much smaller than in eastern North America (66 genera). A study of a glacial map of Europe and North America suggests an explanation. It is seen that at the time of maximum glaciation in Europe the vegetation was confined between the front of the great ice sheet on the north and the expanded mountain glaciers from the east-west ranges (Pyrenees and Alps) at the south. As a result, the less hardy plants were killed, leaving a flora rather poor in species. In eastern North America, on the other hand, the mountain ranges have a north-south direction; and the broad plains offered few obstacles to the migration, back and forth, of plants and animals. In western North America where north and south migration was more difficult, 31 genera of trees are found as contrasted with 66 genera in the east.

On the summits of some mountains arctic plants and insects are found whose presence is difficult to explain except on the assumption that, as the ice retreated northward, they followed the front closely moving up the sides of the mountains as the ice retreated; and that they were stranded there when the ice disappeared from the region.

Attention has been called (p. 644) to the fact that, apparently as a result of the oscillations of climate which marked the Pleistocene, plants were forced to special adaptations and habitats, with the result that there is now little mingling of tropical and subtropical types such as was the case in the Tertiary.

REFERENCE ON VEGETATION

WRIGHT, G. F., — *The Ice Age in North America*, 4th ed., pp. 372–391.

Mammoths and Mastodons. — Perhaps the most characteristic Pleistocene mammals were the mammoth and the mastodon (Fig. 577). The mammoths (Columbian and Imperial) are true elephants, and the mastodon is closely related. They have the same general appearance; the most conspicuous differences being (1) in the teeth, which in the mastodon have large, transverse ridges, but in the mammoth (as in the living elephant) are made up of many plates of enamel, alternating with cement and dentine (Fig. 548, p. 613); (2) in the forehead, which is low in the mastodon and high and bulging in the mammoth; and (3) in the shorter and more massive legs of the mastodon.

The largest specimens of the mammoth (*Elephas primigenius*) exceed in size that of any elephant now living, but their average height was probably not much greater. The mastodon was somewhat smaller than the mammoth. Both were covered with long hair, with probably an undercoating of fine wool. It is known that the mammoth had this additional protection against the cold, but it is not definitely known that the mastodon was thus protected.

The mastodon was abundant in America, possibly as abundant as the buffalo (Clarke); 413 specimens of mammoths and mastodons have been reported from North America, of which 330 are mastodons. The mastodon ranged over the whole of North America. Both lived in America after the disappearance of the ice sheets, as is proved by the burial of their remains in peat bogs on top of the latest drift. The finding of charcoal (perhaps the result of lightning) beneath a mastodon skeleton in New York, and charcoal and pottery at the same level in the same bog, suggests the possibility that man and the mastodon were contemporaneous in America. Drawings upon ivory and sketches on cave walls of the mammoth prove, without question, that *in Europe* man had seen mammoths. Carcasses of the mammoth have been found frozen in the ice in Siberia, where they were so perfectly preserved in this cold storage that the body of one, at least, furnished food for dogs, and perhaps even for man, several thousands of years after its death.

FIG. 577. — Model of mastodon. (Restoration by C. R. Knight under direction of Prof. H. F. Osborn. Copyright, American Museum of Natural History.)

The distribution of the elephant tribe in the New World at that time proves that land connections must have existed between Asia and North America, and between North and South America.

REFERENCES FOR MAMMOTHS AND MASTODONS

HUTCHINSON, H. N., — *Extinct Monsters and Creatures of Other Days*, pp. 270–282.
LUCAS, F. A., — *Animals of the Past*, pp. 177–219.
LULL, R. S., — *Organic Evolution.*

Edentates. — This class is found abundantly in the Tertiary formations of South America, and towards its close developed into gigantic and highly specialized forms which were among the largest animals of that continent. The Pliocene land connections between North and South America permitted some of these large creatures to immigrate to North America, where they lived into the Pleistocene. They never reached the Old World, and in South America their living relatives are small and inconspicuous. Some of the Megatherium (Greek, *megas*, large, and *therion*, a beast) tribe (Megatherium, Mylodon, Megalonyx) which reached this continent attained the bulk of a rhinoceros. What strikes one most in examining the skeleton of a Megatherium (Fig. 578) is its pyramidal shape, the hind legs being massive as compared with the fore, and the backbone rapidly enlarging toward the hind quarters. The Megatherium lived upon leaves and twigs, and when standing on its hind legs could, if necessary, use its tail as the third leg of a tripod, leaving the fore limbs free to pull down branches or even trees of considerable size.

FIG. 578. — Restoration of the gigantic sloth, *Megatherium*. (After Prof. W. D. Scott, *History of Land Mammals*.)

The edentates roamed over South America, and some members of the tribe (Megalonyx and Mylodon) over a large portion of the United States. The finding in Patagonia of a large piece of skin (of Grypotherium) covered with hair, whose edges showed the marks of tools and seems to have been stripped off the carcass by man, indicates that some members of the tribe were alive a comparatively short time ago. But the evidence that man was contemporaneous with the giant sloths in North America is not conclusive.

Another edentate of very different appearance, which is distantly related to the armadillo, is Glyptodon (Greek, *glyptos*, carved, and *odont-*, tooth) (Fig. 579). The body was covered with a bony shell, similar in appearance to that of a tortoise, but made up of a large number of small, polygonal bones united to form an immovable armature, so that this sloth has been called the tortoise armadillo. Not only was the body protected, but the tail also was surrounded by bony plates, and the top of the head was similarly armored. The animals grew to be 15 to 16 feet long. In their migrations they reached Texas and Florida.

FIG. 579. — The great armored sloth, *Glyptodon*. (After Prof. W. D. Scott, *History of Land Mammals*.)

REFERENCES FOR EDENTATES

HUTCHINSON, H. N., — *Extinct Monsters and Creatures of Other Days*, pp. 283–293.
LANKESTER, E. R., — *Extinct Animals*, pp. 167–184.

Matthew, W. D., — *The Ancestry of the Edentates:* Am. Museum Jour., Vol. 12, 1912, pp. 300–303.
Matthew, W. D., — *The Ground Sloth Group:* Am. Museum Jour., Vol. 11, 1911, pp. 113–119.
Scott, W. B., — *A History of Land Mammals in the Western Hemisphere,* pp. 598–625.

Pleistocene Carnivores. — One of the most characteristic animals of the early Pleistocene was the saber-toothed tiger (Figs. 576, 580) (Machairodus), so named because of the enormously developed, sharp-edged, upper canine teeth which in some species extended 10 inches beyond the jaw. An examination shows that if the jaw were constructed like that of other carnivores, a time would come in the evolution of the great canine teeth when biting would be impossible. A more careful study of the jaws, however, reveals the fact that the lower jaw could be dropped straight down, thus permitting the animal to use the full length of its teeth in stabbing its prey. The tribe has had a long history, small ancestral forms with moderate canine teeth being known from the Oligocene.

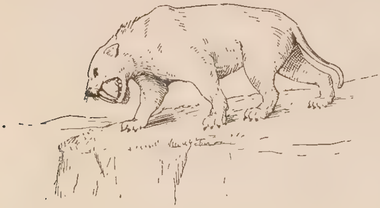


Fig. 580. — Restoration of a saber-toothed tiger. (Modified after Scott.)

Although perhaps the most powerful of the carnivorous animals of the Pliocene and Pleistocene, they nevertheless became extinct early in the Pleistocene in Europe, and disappeared from the New World before the close of the epoch, their place being taken by existing carnivores, such as the lion, tiger, and leopard.

REFERENCE FOR CARNIVORES

Scott, W. B., — *A History of Land Mammals in the Western Hemisphere,* pp. 530–536.

Horses, Camels, etc. — Horses roamed over the plains of North America in great herds and were of great variety, but became fewer and fewer until all had disappeared before the close of the Glacial Period. Some (*Equus giganteus*) had teeth exceeding in size those of the largest modern horses, while others (*Equus tau*) were more diminutive than any other true horses living or extinct.

True camels, as well as llamas, were abundant in portions of the United States in the early Pleistocene, living at least as far north in the United States as Nebraska (Hay Springs) and within the Arctic circle in the Yukon territory. They probably became extinct on this continent before the close of the epoch.

Bisons of many species roamed over North America during the Pleistocene, some of which were of great size, if the horns can be taken as a measure, one pair of horns measuring more than six feet from tip to tip. Wolves, musk oxen, bears, and rodents (among which is a giant beaver, Castoroides), were also present.

Although Europe was not invaded by the sloth tribe, it was, nevertheless, the meeting place of many animals, those of the tropics and those of the Arctic regions coming at different times and even mingling at others.

REFERENCES FOR HORSES AND CAMELS

Camel: International Encyclopedia.
Osborn, H. F., — *Age of Mammals*, p. 484; and others.
Scott, W. B., — *A History of Land Mammals in the Western Hemisphere*, pp. 291–308; 386–402.

Birds. — The Pleistocene birds of Europe and America were not of exceptional size, nor did they differ to any important degree from those now living, but in New Zealand and Madagascar, gigantic flightless birds were abundant during that epoch. The name moa includes, in a general way, 20 to 25 species of these New Zealand birds, the largest of which stood 11 feet high, or from two to three feet higher than an ostrich, while the smallest were about the size of a turkey. In all of these, wings are entirely wanting. The development of flightless birds on these islands seems to be the indirect result of the absence of carnivorous enemies. With an abundance of food throughout the year and no powerful enemies, the New Zealand Pleistocene birds had not the usual incentives to flight. Under such conditions, some of them increased in bodily size until flight was impossible (25 or 30 pounds seems to have been the limit of the weight of flying animals). Once the power of flight was lost, the larger and more powerful the bird the better was the chance of its preservation as long as food was abundant, and great size resulted. A change in climatic conditions, however, was fatal to these bulky birds, since having lost the power of flight they were unable to migrate, and were, therefore, forced to depend upon the food of the islands. Their extinction appears to have been due partly to the cold of the Glacial Period and partly to man who, it is thought, completed their extermination about 500 years ago.

REFERENCES FOR BIRDS

Hutchinson, H. N., — *Extinct Monsters and Creatures of Other Days*, pp. 220–230.
Lankester, E. R., — *Extinct Animals*, pp. 240–244.
Lucas, F. A., — *Animals of the Past*, pp. 138–151.
New International Encyclopedia, and Encyclopedia Britannica.

Prehistoric Man

The record of prehistoric man and his ancestors is a matter of geological as well as of anthropological investigation. Our knowledge of the presence, although not of the evolution, of prehistoric man is far more complete than of other animals, because the source of information is not confined to his bones, but is obtained also from the implements of stone which he made and the discovery of which is especially likely, as they were frequently lost in fishing or in the chase. Moreover, since they are practically indestructible, they are preserved after the skeletons of their makers have been destroyed.

It is a mooted question whether or not man existed in America at an early period, but in Europe the remains of prehistoric man have been found in situations which prove beyond question their antiquity.

A brief classification based on the evolution of human implements in Europe is as follows:

Recent	Iron Age	The Present.
	Bronze Age	Implements of bronze as well as of stone. Some tribes passed directly from the Stone to the Iron Age.
	Stone Age	Neolithic (Greek, *neos*, new, and *lithos*, stone). Implements of stone, often polished and with ground edges.
Pleistocene	Prehistoric in the Old World	Paleolithic (Greek, *paleos*, old, and *lithos*, stone). Stone implements, rough with chipped edges but never ground.
Tertiary		Eolithic (Greek, *eos*, dawn, and *lithos*, stone). Dawn of the Stone Age. Implements so crude that it is often difficult to distinguish them from those made by accident.

Eolithic. — In Pliocene and Miocene deposits and, it is asserted, even in those of the Oligocene, extremely rude flints, called eoliths (Fig. 581), have been found. Although rough and crude, they often show one part shaped as if to be held in the hand, while the other part appears to have been designed for cutting. It has long been a question whether these flints were the result of accident or were made by a "tool-making animal," either very early man or a prehuman type given to shaping implements. If the flints did not occur in deposits earlier than the Pleistocene, the question might be answered more certainly, but since they are found in beds laid down more than a million years ago, the difficulty is increased.

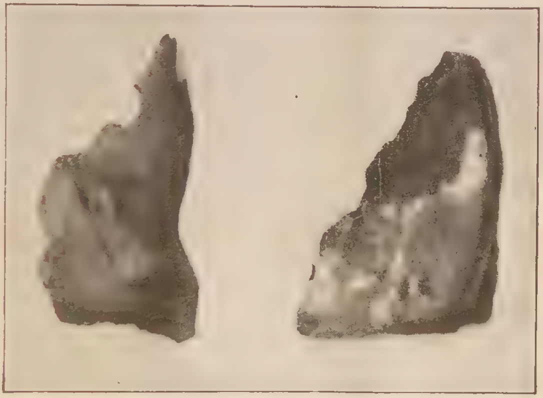


Fig. 581. — Eoliths, the crudest of flint implements. Believed to have been made by ape-men. (After MacCurdy.)

The discovery, near Heidelberg, Germany, of a lower jaw of a very low type in early Pleistocene deposits said to contain eoliths, is important, since it gives a clue to the makers of these flints. This lower jaw is massive, with an essentially human set of teeth, its most noticeable feature being the absence of a chin projection. In other words, it is the jaw of an anthropoid (manlike) ape with the dentition of a man. As compared with the oldest Paleolithic skulls (Neanderthal) (p. 667), this one is of a much lower type. It is possible, therefore, that the eoliths of the later Tertiary were made by some tool-making ape.

A creature (*Pithecanthropus erectus*) whose fragmentary remains have been found in Pleistocene deposits of Java, associated with the bones of extinct animals, may also have been a member of a race which made eoliths. These remains consist of a skull cap, two molar teeth, and a diseased thigh bone, and are remarkable because of the combination of ape and human characters. The skull differs from that of an ape, its brain capacity being about twice that of an ape of equal bodily size. The brain capacity of an ape's skull is, on an average, 500 cubic centimeters; of the skull of this so-called ape-man (*Pithecanthropus erectus*) 850 cubic centimeters; of an average man 1400 to 1500 cubic centimeters. The skulls of aborigines of Tasmania have an average of only 1199 cubic centimeters. This skull, then, as regards capacity, occupies an intermediate position between the large apes and man. Moreover, the forehead is low and the frontal ridge prominent, and the characteristic features are, in general, intermediate between those of the lowest man and the highest apes. The teeth are human, with certain apelike characters, and the thigh bone is considered to be intermediate.

Fig. 582. — On the left, a Paleolithic implement; on the right, a Neolithic implement. (After MacCurdy.)

Paleolithic Man. — Although at first merely chipped into shape and never ground at the edges or polished, the Paleolithic stone implements (Fig. 582 *A*) indicate that their makers had a much greater intelligence and skill than that possessed by the tool-making animals of Eolithic times. The works of Paleolithic man are found principally in caves and in river gravels, often associated with the bones of extinct animals and occasionally with the bones of man himself. It seems to be well established that Paleolithic man, together with other southern animals, reached western Europe during one of the interglacial periods, probably during the second.

The relative age of Paleolithic human relics can often be determined by a study of the fauna with which they are associated. The oldest relics are found with elephants (*Elephas antiquus*) more ancient than the mammoth, very old rhinoceroses (*Rhinoceros merckii*), and hippopotamuses (*Hippopotamus amphibius*). In the next oldest stage the mammoth, woolly rhinoceros, cave bear, cave hyena, and other extinct animals are common. The last stage occurred at the close of the Glacial Period, at which time reindeer were crossing Europe in great numbers; and their remains often occur with those of man, giving it the name of " Reindeer stage."

We are assisted in our conception of Paleolithic man by a study of the recently extinct aborigines of Tasmania, who were, though recent, a true Paleolithic, or perhaps a degenerate race. Their clothing consisted of skins thrown over the shoulders, and they protected themselves from the rain by daubing themselves with grease and ocher. They had no fixed place of abode; and even in winter, a screen of bark served as a shelter. Their implements were few and simple, and were made of wood and stone, the latter being fashioned by striking off chips from one flake with another. Cooking by boiling was unknown; and their sea food consisted of shellfish, as they knew nothing of fishing with a hook. Their survival until the present was due to their isolated position.

FIG. 583. — Skulls of modern and older Paleolithic man. The contrast in forehead, brow, teeth, chin, and shape of skull is very marked.

The skulls and skeletons of the older Paleolithic men of Europe show that they were savages of the lowest type (Figs. 583 *B*, 584), with low foreheads and rather large though not highly organized brains. They were small in stature (five feet, three inches in average height), with knees that were bent slightly forward, giving them a carriage that was not fully erect.

FIG. 584. — Thigh bone of modern man (shaded), and of older Paleolithic man (outline).

The younger Paleolithic men were of a much higher type than the older Paleolithic, and they were not only hunters but artists of a high order. The animals they hunted included the horse, rhinoceros, bison, and reindeer.

The presence of charcoal in the caves of Paleolithic men shows that they knew how to produce fire by friction, and that they probably roasted the flesh upon which they largely subsisted. They apparently knew nothing of agriculture and had no domestic animals, not even a dog. The stone arrows, lance heads, and hatchets, as has been said, were never ground at the edges nor polished. In some caves implements made of bone, such as arrows, harpoons, fishhooks, awls for piercing skins, and needles are not uncommon. The love of adornment is proved by the occurrence of numerous perforated teeth and shells which were doubtless strung into necklaces. The artistic skill displayed in carvings on bone and ivory (Fig. 585), sketches on mammoth tusks (Fig. 586), as well as pictures on the walls (Figs. 587, 588) of their caves, is unexpected, being superior to that possessed by any other primitive men ancient or modern. Indeed, in our own time few people not artists can equal some of the art of Paleolithic man. Although there is no perspective composition in the pictures, the drawing is excellent and the proportions and postures are unusually good. Sketches were made in red and black (Figs. 587, 588), as well as outline drawings in black. The artists chose almost exclusively the large animals of the time, the bison, mammoth, reindeer, horse, boar, and rhinoceros. Man for some reason was seldom portrayed. During the Paleolithic the making of flint implements was gradually perfected, and before its close bone and horn implements of highly useful and artistic forms were made.

Fig. 585. — Carvings on bone made by Paleolithic man.

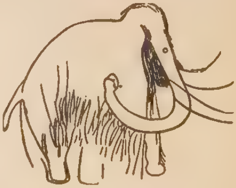


Fig. 586. — Paleolithic carving of a mammoth.

Paleolithic man had a crude form of religion, and the dead were buried ceremoniously. There appears to have been a division of labor, some men devoting themselves to hunting, some to flint making, and some to art, although it is hardly probable that the specialists in any of these groups were not often employed in other work.

Neolithic Man. — Man of Neolithic times was not contemporaneous with the great extinct mammals, with the exception of the Irish elk. Their remains have been found in caves, cemeteries, and river deposits, in peat bogs, and lake bottoms (pile dwellings), and in shell mounds. Neolithic implements and weapons are often ground at the edge (Fig. 582 *B*) and more or less polished and finely finished, and are frequently of graceful design. With some doubtful exceptions, Paleolithic man in western Europe seems to have been suddenly replaced by Neolithic man, who brought with him not only greater skill in the manufacture of implements, but domesticated animals, such as the dog, horse, sheep, goat, and hog. Moreover, he was acquainted with agriculture, as grains and the seeds of fruits, as well as dried fruits, show. Spinning, weaving, and pottery making were also practiced.

Fig. 587. — Paleolithic painting of a boar. (Courtesy, American Museum of Natural History.)

Fig. 588. — Paleolithic painting, in red and black, of a bull. (Courtesy, American Museum of Natural History.)

An important part of our knowledge of Neolithic man comes from the lake dwellings in Switzerland and Sweden. These dwellings were on piles driven into shallow lakes, and were connected with the shore by drawbridges which could be withdrawn in case of attack.

The Age of Stone gradually merges into the Bronze Age, as that, in turn, merges into the Age of Iron, but since these last two stages belong to protohistorical and historical times, they are outside our province. The Age of Stone did not come to an end throughout the world at the same time. The natives of the New World, Australia, and the islands of the Pacific were in the Neolithic Age, and those of Tasmania in the Paleolithic Age, when discovered by Europeans; and some isolated tribes are to-day still using stone implements.

REFERENCES FOR PREHISTORIC MAN

Anthropology and Archæology: Encyclopedia Britannica.
BOULE, M., — *Fossil Men,* 1923.
BURKITT, M. C., — *Prehistory.*
DECHELETTE, *Manuel D'Archeologie,* Vol. 1.
DUCKWORTH, W. L. D., — *Prehistoric Man,* 1912.
HOERNES, MORITZ, — *Kultur der Urzeit,* Vol. 1, 1912.
KEITH, ARTHUR, — *Ancient Types of Man.*
MACALLISTER, R. A. S., — *A Text Book of European Archeology,* Vols. I and II.
MACCURDY, G. G., — *Human Origins,* 1924.
MUNRO, ROBERT, — *Paleolithic Man and Terramara Settlements in Europe.*
OBERMAIER, HUGO, — *Fossil Man in Spain,* 1924.
OSBORN, H. F., — *Men of the Old Stone Age.*
PARKYN, E. A., — *Prehistoric Art.*
REINERTH, HANS, — *Pfahlbauten am Bodensee,* 1922.
SCOTT, G. F. ELLIOT, — *Prehistoric Man and his Story.*
SOLLAS, W. J., — *Ancient Hunters,* 1924.
TYLER, J. M., — *The New Stone Age in Northern Europe.*

Man in North America. — No conclusive proof of the presence of man in North America during the Pleistocene has yet been offered. Indeed, it is doubtful if Paleolithic man ever lived on this continent.

Earlier investigators were led to assign a greater antiquity to many human relics than subsequent study has shown to be possible. Such errors were the result of over-enthusiasm and a failure to take into consideration all of the elements of the problem, some of which are the following.

(1) The presence in river gravels of rude flints has led to the conclusion that they were made by Paleolithic man. The danger in such a conclusion lies in the fact that, in the shaping of a stone tool the maker sometimes loses the half-finished stone and often rejects others early in his work because of some imperfection or unfavorable quality in the stone. As a consequence, many unfinished stone im-

plements are left, especially along river courses where the pebbles from which the implements were made occur.

(2) If a stone implement is found buried to a great depth, the thickness of the overlying deposit has often been taken as a measure of its age. Such data are very uncertain, since during floods a river may scour out deep holes in its bed, and within a few weeks, or months, completely fill the excavation. The Missouri, for example, scours out its bed to a depth of 40 feet or more during floods, and soon fills it again (p. 88). It will readily be seen, therefore, that the finding of a flint implement in river gravels at a depth of 40 feet might not indicate any greater antiquity for it than for one on the surface.

(3) The age of flints in talus slopes is uncertain, since what was in the top portion of the cliff naturally becomes part of the base of the talus as the cliff crumbles back.

(4) The antiquity of stone implements found beneath layers of stalagmite has often been overstated, because a too low rate of deposition was used in the estimate. This, however, has not been a source of difficulty in America, since cave deposits are rare on this continent.

(5) The admixture of human remains with those of extinct animals is not necessarily a proof of their contemporaneousness, since it may have been due to accidental causes, such as human burial in deposits containing extinct animals, or to the washing out from older deposits of the bones of extinct animals and their redeposition with those of recent species.

It will readily be seen from the above that the error in determining the age of human relics will usually be in the direction of too great antiquity. From the similarity in physical appearance of the aborigines of North and South America, it seems probable that the original inhabitants of the New World were immigrants who came from Asia and spread over the Americas after they had become differentiated in Asia, but long enough ago to permit of the development in their new home of the many languages and dialects now spoken by the Indians.

REFERENCES FOR MAN IN NORTH AMERICA

Osborn, H. F., — *Age of Mammals*, pp. 494–500.
Osborn, H. F., — *Men of the Stone Age*.
Scott, W. B., — *A History of Land Mammals in the Western Hemisphere*, pp. 588–590.
Wissler, C., — *The Art of the Cave Man:* Am. Museum Jour., Vol. 12, 1912, pp. 289–295.

Birthplace of Man. — The location of the original home of man was a matter of speculation even by the ancients and is still in doubt, but some suggestions have recently been made which are worthy of consideration. Science points, as does the biblical account, to Asia as the birthplace of man. It is evident that the Americas were not populated by man until comparatively recent geological times (p. 680), and that Paleolithic and Neolithic man probably migrated to Europe from some other continent. It is a suggestive fact that all of our domesticated animals, with the exception of the llama, the vicuna, and the turkey, had their origin in Asia, and that they are the most highly specialized of their kinds. Moreover, possibly all of the cereals, with the exception of maize, are of Asiatic origin. "Man was born and attained elemental civilization in Asia because there was the place of all others upon the earth where evolution, in general, of organic life reached its highest development in late Cenozoic times." (Williston.) The loss of man's hairy covering is evidence of his origin in a temperate, or cold temperate climate, where he found clothing necessary to protect himself from the inclemencies of the weather.

REFERENCE ON THE BIRTHPLACE OF MAN

Williston, S. W., — *The Birthplace of Man:* Pop. Sci. Monthly, Vol. 77, 1910, pp. 594-597.

Effect of the Advent of Man. — The appearance of man was one of the greatest events in the whole history of the world, not only because, for the first time, brute strength and agility were at a disadvantage in a struggle with higher intelligence, but also because of the changes which he directly, or indirectly, caused, not only in the life of the world, but also in the very topography of the earth itself. (1) Man has directly caused and is still causing the rapid disappearance of many animals: such as the bison, the moa, seal, whale, fur-bearing animals, and the big game of Africa and Asia. (2) Indirectly, by the introduction of animals and plants into new regions, he has accomplished as great, or even greater, changes in life. The introduction of the mongoose into Cuba, which soon destroyed not only the snakes, but the birds that nested on the ground, has almost revolutionized the fauna of that island. The rabbits brought to Australia have overrun that continent, with a marked effect on the indigenous life. The various insects introduced into North America by man are changing the flora of this country. Many other examples might be added. (3) His work has not, however, been entirely destructive to life. Animals and plants on the verge of extinction have been preserved. The ginkgo tree (p. 567), for example, would have been to us an extinct species if man had not preserved it by cultivation. (4) Not only has his contact with the life of the world been important, but his indirect effect upon inanimate nature has been stupendous. The cutting and burning of forests in certain regions has resulted in the rapid erosion of large areas, and the pulverization of the soil in plowing has permitted rainwash to carry away the best of the soil. By deforestation alone a single lumber merchant may in 50 years deprive the human race of soil that required thousands of years to form. Another effect which will eventually greatly lessen the fertility of the soil is the enormous and irrecoverable loss of phosphates in the sewerage of cities. As the result of these and many other effects of man's supremacy, the earth has suffered a vastly greater change in the past few hundred years than in many thousands of years in the most destructive periods of the past.

Future Habitability of the Earth

Two statements are often made concerning the future of the earth: one that the climate will become progressively cooler until it will be unsuited for the existence of plants and animals; the other, that the earth will eventually be consumed by fire. The former statement is based on the assumption that the heat of the sun is diminishing, and that, since the earth depends upon it for its heat, a cooling of the sun will cause refrigeration. There is no question but that this would be the case were the sun's heat to decrease, but no such change can be detected. The present heat of the sun is apparently maintained by the infalling of meteorites, as well as by that given off by radioactive minerals, and, consequently, sufficient heat to produce a favorable climate may exist for many millions of years. A convincing proof lies in the fact that, since life began, the climate has not changed sufficiently to cause a widespread destruction of life. Periods of aridity, glaciation, and other climatic changes have frequently occurred, but none that was universally fatal.

The statement that the earth will eventually be consumed by fire assumes that the sun or earth may collide with some other star. No such catastrophe, however, has occurred in the past, none seems to be impending. It seems safe, consequently, to predict that for many years — hundred of thousands, perhaps millions — the conditions favorable to man's existence will be present.

When it is remembered that man has come up from the cave and the stone hammer in the past 50,000 or 75,000 years, and that in the past 100 years the greatest achievements of science have been accomplished, so that man to-day lives under conditions radically different from those of his ancestors of a few generations past, it would seem that the evolution which will take place will change profoundly the human race, if not interfered with. The progress of evolution does not, however, have a free course since, as never before in the history of animal life, the unfit do not disappear in the struggle for existence, but the life of the physically and mentally unfit is lengthened through the aid of medical science and charity. The future will, doubtless, bring solution for such vital problems.

APPENDIX

COMMON MINERALS

Every student of geology should be able to recognize the common minerals by sight and know their approximate chemical composition. In order to determine minerals without the aid of chemical tests, one must depend upon their physical properties. Of these the color, streak, hardness, specific gravity, and crystalline form are important.

The *color* sometimes varies greatly in the same mineral, but nevertheless often affords a strong clue to its identity. The color of a mineral is often due to the inclusion of foreign matter, such as iron oxide and organic matter, but some minerals, such as the carbonate of copper, malachite, vary slightly.

Each mineral has a characteristic *hardness* and this quality often affords an easy means of positive identification. The scale of hardness in common use is: 1, Talc; 2, Gypsum; 3, Calcite; 4, Fluorite; 5, Apatite; 6, Orthoclase; 7, Quartz; 8, Topaz; 9, Corundum; 10, Diamond. Minerals with a hardness of 1 and 2 can be scratched with the finger nail. If a mineral will barely scratch a copper coin, it may be considered as about 3 in hardness; if it fails to scratch glass, its hardness is less than 5; if it scratches glass but fails to scratch quartz, its hardness is between 5 and 7. A knife point is almost indispensable in determining hardness, since with a little practice, the hardness of all minerals between 1 and 6 can be readily determined.

The *streak* or mark that a mineral makes on a hard white substance, such as a piece of unglazed porcelain, is often important in distinguishing between minerals. The color of the streak is the same as that of the fine powder.

When a mineral breaks or *cleaves* in definite directions so as to form plane surfaces, it is said to have a *cleavage*. Since cleavage is caused by the separation along and between layers of molecules, it occurs only in crystals. The thin leaves of mica are formed by the splitting of the mineral along cleavage planes.

The relative weight of a mineral, or its *specific gravity*, is often an important aid in determining a mineral by its physical properties.

IRON MINERALS

Magnetite (magnetic iron ore), Fe_3O_4. — Color, *black*. A *black streak* is made when the mineral is scratched on a hard white surface. The *hardness* is slightly *greater than steel* (H = 6). It is always *attracted by a magnet* and is sometimes capable itself of lifting particles of iron and steel. It is a valuable ore of iron. The Adirondack iron ore is largely magnetite.

Hematite (red iron ore), Fe_2O_3. — The color is *black* to *brick red*. Streak, *red*. *Slightly harder than steel* (H = 6). Occurs in compact masses composed of micalike flakes, in an earthy form, and in thin crystals set on edge. It is the most widely used iron ore in North America, the most famous localities of which are in the Lake Superior region and in Alabama.

Limonite (brown hematite, iron hydroxide), $2\ Fe_2O_3 \cdot 3\ H_2O$. — The color is usually *dark brown*, but is sometimes *yellow*. The streak is *yellow*. The hardness of compact kinds is *slightly less than steel* (H = 5). The *ocher* which occurs with limonite is composed of clay and limonite in a finely divided condition. Limonite is really iron rust and is formed from the hydration of many iron minerals, and consequently occurs in many situations and is widespread. It is an ore of excellent quality, but is little used in this country because of the more abundant and more easily mined hematite. It is common in New England and the Appalachians.

Siderite (spathic ore), $FeCO_3$. — The color is *gray* on freshly broken surfaces; surfaces exposed to the weather, even for a few weeks, are *brown*. The streak is *white*, or nearly so. It can be *easily scratched with a knife* (H = 4). It occurs commonly in masses which show *shiny, bent, cleavage* surfaces. Siderite effervesces with warm hydrochloric acid, giving off carbon dioxide. It is an ore of iron which, however, is little used in the United States.

Pyrite or Iron Pyrites (fool's gold), FeS_2. — The color is *brass-yellow* when fresh, but oxidizes on the outside to *brown* limonite. It is *harder than steel* (H = 6.5). It occurs in veins and is disseminated throughout many igneous and sedimentary rocks. It often occurs in cubical crystals or in crystalline masses. The yellow stains on rocks are often due to the weathering of grains of pyrite. Pyrite is a common mineral. It is not used as an ore of iron, but is used in the manufacture of sulphuric acid.

Pyrrhotite (magnetic pyrites), $Fe_{11}S_{12}$. — The color is *bronze-yellow* when fresh, but weathers readily to brown on the outside. It is *darker than pyrite.* Pyrrhotite is softer than pyrite and can *easily be scratched with a knife* (H = 4). Small fragments are attracted by a magnet. Pyrrhotite is of little use in itself but, since it often bears nickel, it is mined for that metal. The most valuable deposits occur in Canada, but large quantities are found in Vermont, Pennsylvania, and elsewhere.

Zinc Minerals

Sphalerite (blend, black jack, jack, zinc sulphide), ZnS. — The color varies from yellow to *brown-black.* When a fragment is crushed, the pieces look like resin. This *resinous luster* can usually be seen whenever a specimen is fractured. The streak is *light yellow.* Sphalerite is *softer than steel* (H = 3.5) and occurs in crystals or in masses with well-developed cleavage faces. It is an important ore of zinc and is often associated with lead and silver ores. It is extensively mined in Missouri and is of common occurrence in smaller quantities elsewhere.

Calcium Minerals

Calcite (calc spar), $CaCO_3$. — The color, when pure, is *white* or *colorless*, but when impurities are present the color depends upon the foreign substance; yellow, green, gray, salmon, lavender, and other colors are common. Calcite is *much softer than glass* (H = 3). It is readily distinguished from other minerals by its strong *rhomboidal cleavage*, its *hardness*, and its *effervescence with acids.* It is one of the most widespread and abundant minerals. There are a number of varieties, including *dogtooth spar*, so-called because of the shape of the crystals; *marble*, a crystalline rock composed of large and small grains of calcite; Mexican *onyx*, an agatelike rock formed by successive layers of lime deposited from solution in a cavity.

Dolomite (pearl spar), $CaMg(CO_3)_2$. — The color is usually *white* or with a yellow tint. It is *softer than steel* (H = 3.5). Dolomite is distinguished from calcite, which it resembles, by its *curved cleavage surfaces*, its *pearly luster*, and its *lack of effervescence* with cold hydrochloric acid. It occurs in distinct crystals and forms thick strata of limestone. It is a common vein mineral.

Gypsum, $CaSO_4 \cdot 2\,H_2O$. — This mineral is *colorless* or *white* unless tinted by impurities. It is softer than calcite and can be *scratched* *with the finger nail* (H = 2). Gypsum occurs in veins or beds; in crystals, or compact, rocklike masses. The most important variety is *selenite*, a crystalline gypsum with a perfect cleavage, thin leaves of which may be split off and resemble those of mica. They differ from the latter in their inelasticity and vertical cleavage. *Alabaster* is a compact, fine-grained, usually translucent gypsum, used in making ornaments and statuary. *Satin spar* is a fibrous gypsum which has somewhat the appearance of satin. It is occasionally used in the manufacture of cheap jewelry. *Rock gypsum* is compact and rocklike. It is used for plaster of Paris. Gypsum is common in many portions of North America, but is especially abundant in New York, Iowa, Michigan, and Ohio.

Fluorite (fluorspar, blue john), CaF_2. — The color is commonly *blue* or *green*, but is occasionally white or yellow. It is slightly harder than calcite and can be *scratched with a knife* (H = 4). Its principal use is as a flux in reducing iron, but it is used to some extent for ornamental purposes. It occurs in clear, cubical crystals, and in masses. Fluorite is mined in Illinois and Kentucky.

Apatite (asparagus stone, phosphate rock, calcium phosphate). — The color is usually *green* or *reddish brown.* It is harder than fluorite and *cannot easily be scratched with a knife* (H = 5). After being treated with sulphuric acid, it becomes a valuable fertilizer. It is found in many parts of North America, but the most valuable deposits occur in Canada.

COPPER MINERALS

Chalcopyrite (copper pyrites), $CuFeS_2$. — The color is a *deeper yellow than pyrite.* Chalcopyrite can be *easily scratched with a knife* (H = 3.5) and this character alone easily distinguishes it from pyrite, but not from pyrrhotite. The bluish tarnish of chalcopyrite is also distinctive. Since it is not attracted by a magnet, it is easily distinguishable from pyrrhotite. It is a valuable and widespread ore of copper and is mined in many of the Western States.

Malachite (green copper carbonate), $(CuOH)_2 CO_3$. — The color is *bright green.* The *color*, *hardness*, which is *less than that of steel* (H = 3.5), and its *effervescence with acids* readily distinguish it from other minerals. Its principal use in the United States is as an ore of copper, although in Europe the compact varieties have long been much sought after for vases, table tops, and mosaics.

LEAD MINERALS

Galenite (galena), PbS. — The color is *lead gray.* Its softness (H = 2.5), its *high specific gravity* which is greater than that of iron, and its *strong cubical cleavage* make it one of the most easily recognizable minerals. It occurs in masses and as cubical crystals. Galena is valuable as an ore of lead, as well as for the silver which it usually carries.

SILICA MINERALS

Quartz and its Varieties, SiO_2. — When pure, quartz is *colorless* or *white*, but in no other mineral do the colors vary so widely; red, pink, yellow, brown, green, blue, lavender, and black, in fact almost every conceivable color is found in quartz. Quartz is *harder than steel and scratches glass* (H = 7). It is the commonest of minerals. "It makes up most of the sand of the seashore; it occurs as a rock in the forms of sandstone and quartzite, and is a prominent part of many other important rocks, as granite and gneiss." It is readily distinguished from other minerals by its *hardness* and its *lack of cleavage.* The crystals are six-sided (hexagonal). The principal varieties are: *rock crystal,* as the clear quartz crystals are called, which is used for making "pebble lenses," "Japanese balls," and other objects; *amethyst,* purple crystalline quartz which is cut for gem stones; *rose quartz,* which is light pink or rose color; *milky, smoky,* and *yellow* quartz, named because of their color. *Chalcedony* is a translucent variety with a waxy luster which varies greatly in color. *Agate* is a banded chalcedony in which the bands are variously colored. *Flint* (p. 524) and *chert* are gray to black translucent or opaque quartz masses which occur in chalk and limestone. *Jasper* is similar to flint in appearance, but is usually red, black, white, or yellow.

SILICATE MINERALS

Orthoclase Feldspar (potash feldspar), $KAlSi_3O_8$. — The color is usually *white, gray, or flesh.* The hardness is *about that of steel* (H = 6). The mineral *cleaves* readily, the cleavage planes being at right angles to each other. Orthoclase feldspar is an important constituent of granite and sometimes occurs in large crystals. Pure feldspar is used to make the glaze on porcelain.

Labradorite Feldspar (lime feldspar). — The color is *dark gray, often with blue, green, and red iridescence.* It is *slightly harder than steel*

(H = 6). The *cleavage planes are often striated* and are *not at right angles* to each other as in orthoclase. It is an important constituent of some igneous rocks. Labradorite is used to a limited extent for ornamental purposes.

Muscovite Mica (isinglass, white mica), $H_2KAl_3(SiO_4)_3$. — It is usually *transparent or gray.* It can be *scratched with the finger nail* (H = 2). The most distinctive characters of muscovite are its ability to be *cleaved* into thin leaves, its *hardness*, the *elasticity of its leaves*, and its *color.* It is used in stove doors, for insulation in electrical apparatus, and, when ground, as a lubricant.

Biotite Mica (black mica), a complex silicate. — With the exception of the color and chemical composition, biotite has the same characters as muscovite.

Chlorite, a complex silicate. The color is usually *dark green.* It is so soft that it can be *easily scratched with the finger nail* (H = 1–2). It occurs in *dark green masses in which the flakes are usually so small as to be distinguished with difficulty.* Chlorite occurs commonly in metamorphic rocks.

Talc, a hydro-magnesian silicate. — The color is *white, greenish, or gray.* It is readily distinguished by its *soapy feel* (H = 1), in which it differs from gypsum. Talc commonly occurs in plates or leaves like mica. It occasionally occurs in beds 15 or more feet in thickness. It is ground to make " talcum powder " and has many other uses, such as a filler for paper, a lubricant, and an adulterant. Large deposits of talc occur in New York, Massachusetts, North Carolina, and other states.

Serpentine, a hydro-magnesian silicate. — The color is usually *green or yellow*, and the hardness is *less than that of steel* (H = usually about 3). There are two principal varieties, *massive serpentine*, a compact mineral with a *greasy or waxy luster*, and *asbestos* or *chrysotile*, a fibrous variety. The massive serpentine is polished for table tops and other ornamental purposes; the asbestos is used in the manufacture of fire-proof articles, such as theater curtains, coverings of steam pipes and boilers, and for firemen's suits. The province of Quebec is the great center for asbestos.

Hornblende, a silicate of several elements. — The color is commonly *black*, and the hardness *about that of steel* (H = 5.6). The most distinctive character of hornblende is its occurrence, usually, in *slender, flat crystals*, the larger angles of the crystals being about 124 degrees. A fibrous variety known as *hornblende asbestos* has much the same appearance, and is used for the same purpose, as serpentine asbestos. Hornblende is a constituent of some igneous rocks.

Augite, a silicate of several elements. — The color is *black* or *dark green* and the hardness *about that of steel* (H = 5–6). It usually occurs in *short, thick crystals.* It is a rock-making mineral of wide distribution and is an important constituent of "trap."

Olivine (chrysolite, peridot), an iron magnesium silicate. — The color is usually *yellowish green*, and the hardness that of quartz (H = 6.5–7). It is an important constituent of some igneous rocks. Large, clear crystals are cut for gem stones.

Garnet, variable silicates of various bases. — The color is commonly *red* or *black*, but brown and green garnets also occur. The hardness is *that of quartz* (H = 7). Garnets usually occur in crystals with 12 similar faces (dodecahedrons or trapezohedrons) and are found embedded in metamorphic rocks of various kinds. Garnets are crushed and manufactured into sandpaper, and fine, clear specimens of good color are cut for gem stones.

INDEX

INDEX

Sam Carter
University of Toledo
K. I. ~~K~~ K, I, K,

TOLEDO OHIO

The How Book,
Headquarters U.S.A.

Test or first Exam after
Vacation - very soft.
Also classes ([illegible])

Yellow stone falls
Proportions of Sol to reserve etc.

Apply to Ships going to Hawaii - work way across
stay week at Hawaii.

3-5 Minute Talk for Geology
or
Any Subject. Next Class.
Also a thought for each class recitation
as contribution

Pg 294-311

Values